Flexible and Spectrum-Aware Radio Access through Measurements and Modelling in Cognitive Radio Systems

FARAMIR

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Abstract:

The objective of the FARAMIR project is to research and develop techniques for increasing the radio environmental and spectral awareness of future wireless systems. Radio Environment Maps utilized by Cognitive Radios form the foundation of the work, which is further complemented development of new spectrum sensing techniques, data processing algorithms, and applications such as radio resource management solutions. The project aims to take a practical approach and prototype the project innovations showing their real-world value in radio resource optimisation. Additionally, extensive spectrum measurements will be conducted at several locations in Europe to provide a valuable basis for spectrum modelling and increase the understanding how spectrum use changes in time, frequency, and space. The purpose of this State-of-the-Art review document is to survey earlier work in the field with respect to the above issues, and specifically to highlight areas in which further research or measurement work is needed. The document will also serve as a guide to the relevant literature, seeking to present key concepts and research results in a harmonized manner. As a part of this effort extensive list of terminology has also been collected and reported in this document.

Keywords: Cognitive Radio, Cognitive Networks, Radio Environment Maps, Spectrum Sensing, Spectrum Sharing, Resource Management, Spectrum Measurements, CN Testbeds, Regulatory issues

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Contents

1 Introduction

Cognitive Radios (CR) and their resulting Cognitive Wireless Networks (CWN) have recently become one of the most intensively studied paradigms in wireless communications. In this report we take "cognitive radio" to mean a context-sensitive and adaptive radio, as originally defined in Mitola's seminal work, capable of observing its environment and configuring itself optimally for whatever communications task is at hand. An important specific application often associated to cognitive radios is Dynamic Spectrum Access (DSA). The classical meaning of DSA is the (re)-use of licensed radio frequencies by cognitive radios ("secondary users"), provided that the license holder ("primary user") is not using those frequencies at a given time or in a given region of space, thus leaving that portion of the spectrum temporarily empty and available for the secondary user. Work on DSA has in fact become so prominent that DSA is often taken as the defining characteristic of a cognitive radio. However, this is a limiting view since it would rule out many of the interesting application areas for cognitive-radio technologies in, for example, self-organizing wireless networks such as emerging femtocell deployments. Thus, although the project is strongly emphasizing DSA scenarios, we will also explore applications of the general cognitive-radio principles in various other wireless network types, including classical mobile wireless networks.

For both general cognitive radios as well as for cognitive devices limited to basic DSA, environmental (radio) knowledge can be used to significantly enhance the associated decision-making and resource-management processes. Information on location of transmitters, propagation conditions, or activity patterns of different transmitters can all be used to help make decisions on transmit power and modulation to be used, to guide the sensing process in DSA scenarios, or to choose appropriate MAC layer parameters, to name a few examples. The key objective of the FARAMIR project is to enable and enhance the gathering, storing and applying of such environmental information in the context of cognitive radios and DSA networks. Towards this purpose, Radio Environment Maps (REMs) are emerging as the main enabling technology in this process, acting as a broad database in which environmental information is stored and processed, and from which it can be subsequently accessed by various interested parties and users (for example, cognitive radios, but not only those).

While the REM concept has appeared in the research literature before, there has been very little concrete engineering design towards actually deployable and implementable solutions, a situation FARAMIR seeks to remedy. On the other hand, there has been a large volume of good research and development work for many of the enabling technologies for REMs such as spectrum sensing and modeling of environmental data, as well as the various applications of data stored into the REMs. The objective of this state-of-the-art (SoA) review document is to provide a comprehensive summary of this work, especially focusing on these enabling technologies, in order to serve as a foundation for the successive work to be done in the project. There exist already a number of review articles in cognitive radios and specific enabling technologies such as detection technologies, and, moreover, several recent books have been published [1]-[5]. We avoid duplicating too much of the existing work in this deliverable, thus if publicly available review material is already available we mostly refer the reader to that material. However, there are some specific areas, such as REMs, which are not adequately covered by the existing introductory material and this deliverable aims at to correct those issues for the benefit of the project.

The report is structured as follows: in Sections 2 and 3 we first provide a concise overview of some of the key usage scenarios for cognitive radio technologies and DSA networks. The objective of this part is to highlight the diverse applications that REMs can enable, both in dynamic spectrum access networks as well as in general cognitive wireless networks, and to set up terminology for the rest of the document. We then move on to discuss the role of REMs in the selective scenarios presented in Section 4, specifically focussing on the types of information to be stored in them, as well as challenges in designing and implementing REMs for different application scenarios. The rest of the report, namely Sections 5 to 9, will then review the SoA of the different enabling technologies related to either providing information into REMs, processing it, or applying it in different resource-management tasks. Related testbed activities, measurement campaigns on spectrum use, as well as standardization activities connected to REMs are also discussed in these Sections. Due to the space limitations and the need to keep a reasonable focus, these Sections concentrate on a carefully selected subset of all the possible topics, giving references to other reviews where needed to complete the picture. The report is finally concluded by a summary of the key findings in Section 10, especially highlighting areas in which new research needs to be carried out in order for the project to be able to reach its goals.

Key contributions of this document are reviews of many of the CR- and REM-related technologies not covered yet in detail in earlier review papers (as far as we are aware). These include, for example, detailed discussion on the different aspects of general radio environment map architecture design and the related data processing issues, as well as new concepts injected into spectrum sensing such as directionality, and neighbourhood-based approaches. This document will also serve as a handbook of terminology (given in Annex I) and concepts for the project in order to ensure consistency and clarity for future research reports.

2 Scenarios and Usage

Before entering into a deeper technical discussion on cognitive radios, radio environment maps and their various technical enablers, we shall briefly look into some of the key usage scenarios for these technologies. State-of-the-art scenarios for the use of cognitive radio are described in a number of standardization efforts, [6]-[10], and ongoing (European) research projects [11], [12] along with other non-profit corporations [13]. As a common element, all these usage cases implicitly pre-suppose a reconfiguration ability ("reconfigurability") of the radio equipment (either at the network side or at the terminal side, or both) in terms of parameters such as operating frequency, bandwidth, or Radio-Access Technology (RAT).

In general, the different scenarios are based on three basic area of classifications or viewpoints that dominate the use of DSA and Cognitive Radio systems either as limitations or opportunities. These classification areas are:

- Regulatory and license rule issues;
- Economical considerations and business models, including the services to be offered; and
- Technological possibilities and opportunities.

There exists a quite large amount of literature to consider these different aspects, especially in the domain of regulatory and economical impacts [14]-[24]. Also some European projects, such as recently started QUASAR-project, are assumed to tackle this problem space. The explicit scenarios and the classification are not critical for FARAMIR, except to specify prototypes and exploitation models. This is so because FARAMIR is focused mostly to providing enabling technologies that are applicable for most of, if not all, possible scenarios covering the above classification areas. This is particularly true for REM, spectrum detection and directional awareness systems. Nevertheless, in order to set the scene for the following sections, we present a selection of key usage scenarios for cognitive radios.

Regulatory issues are dominantly present in any discussion on cognitive radio. Therefore, in the following we categorize the various usage cases and scenarios according to the licensing policies relating to the relevant frequency bands. This classification aligns to a large extent with those made in [6] and [7].

2.1 *Dedicated Spectrum (Licensed) Scenarios*

In this class of scenarios, all relevant spectrum is assumed licensed. In particular, one or more operators are each assigned exclusive rights for the use of dedicated portions of radio spectrum. Examples that belong to this group are scenarios in the ETSI RRS draft report [6], the scenario in Annex A of IEEE standard 1900.4 of the SCC-41 [7], and the scenarios given in the ITU report [8]. All of these scenarios fall into a smaller number of general classes, characterised by the following usages of cognitive radio technologies.

Software defined multiradio in (end-user) mobile devices: This scenario assumes that software-defined multi-radio technology is used to realize reconfigurability of radio equipment in mobile devices (end-user terminals). A reconfigurable radio is capable of, among other things, scanning the radio frequencies and making an autonomous selection of radio (access) technology based on user preferences.

Radio (access) technology selection in composite wireless networks: In this scenario, an operator utilizes multiple radio (access) networks in different frequency bands all assigned to the operator under existing regulation, and that operator wishes to combine all these individual radio networks into a single composite network. By monitoring the traffic load on these different radio networks, the cognitive network management system can decide on the assignment of users to different radio (access) technologies in a dynamic manner, something which leads to optimal use of the composite capacity of the frequency bands. This scenario is also applicable to a situation where the radio networks are not owned by a single operator but several operators wish to cooperate in order to manage their composite radio networks jointly and efficiently.

Radio resource usage optimization in composite wireless networks: In this scenario, one or more operators own multiple radio-access networks in different frequency bands. Radio nodes on the network side of these radio access networks as well as the terminals are often assumed to have reconfiguration capability via, for instance, software-defined radio technology. These reconfigurable radio nodes on the network side dynamically adjust their operational parameters and/or radio resources in order to meet some predefined objectives (e.g., increase capacity and improve QoS) and according to current radio regulations. The same general principles can, however, be applied also in the case of legacy Radio Access Networks (RANs), either in centralised fashion, or arranging decision making on reconfiguration of terminals to be performed in a distributed manner in order to optimize radio resource usage and improve QoS.

Cooperative spectrum access between operators: In this scenario the emphasis is not in reconfiguration or management of the networks of the individual operators, but enabling more efficient resource usage, and especially spectrum usage, between operators. Techniques relevant to this scenario include a variety of dynamic spectrum sharing schemes, such as market-based mechanisms, spectrum brokers, etc.

In summary, the key objective in this class of usage cases is the optimization of the radio resource among different operators and/or among different radio-access networks. The usage case A.3 in [7] as well as case 4 in [8] describe examples where, by appropriately reconfiguring terminals connected to different networks, an originally unbalanced usage of radio resources can be improved. Figure 1 illustrates the idea.

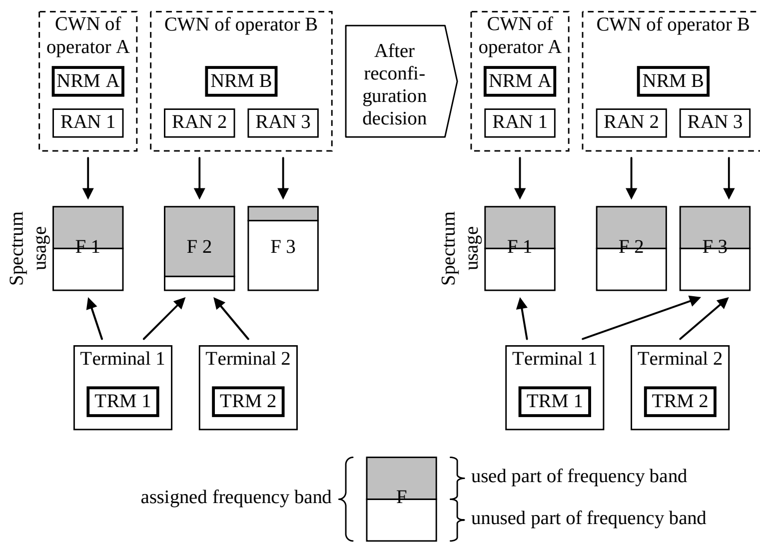


Figure 1: Example of radio resource usage optimization [7].

Based on what is referred to as *context information* (essentially, any piece of information other than policies needed for decision making on the optimization of radio resources), a network reconfiguration manager establishes at any point time a desirable distribution of the radio resource usage over these different networks and/or over different operators.

2.2 *Shared (License-Exempt) Scenarios*

This class of scenarios and usage cases is associated with license-exempt spectrum. Users access the spectrum autonomously, whenever and wherever they wish. This kind of spectrum-sharing already exists in the ISM bands where, for example, equipment for the IEEE 802.11, DECT and the Bluetooth standards all access the same spectrum. The introduction of cognitive concepts in these systems seems therefore rather straightforward. The usage case U.1: “Cognitive radio networks on unlicensed bands” reported in [6] describes this scenario.

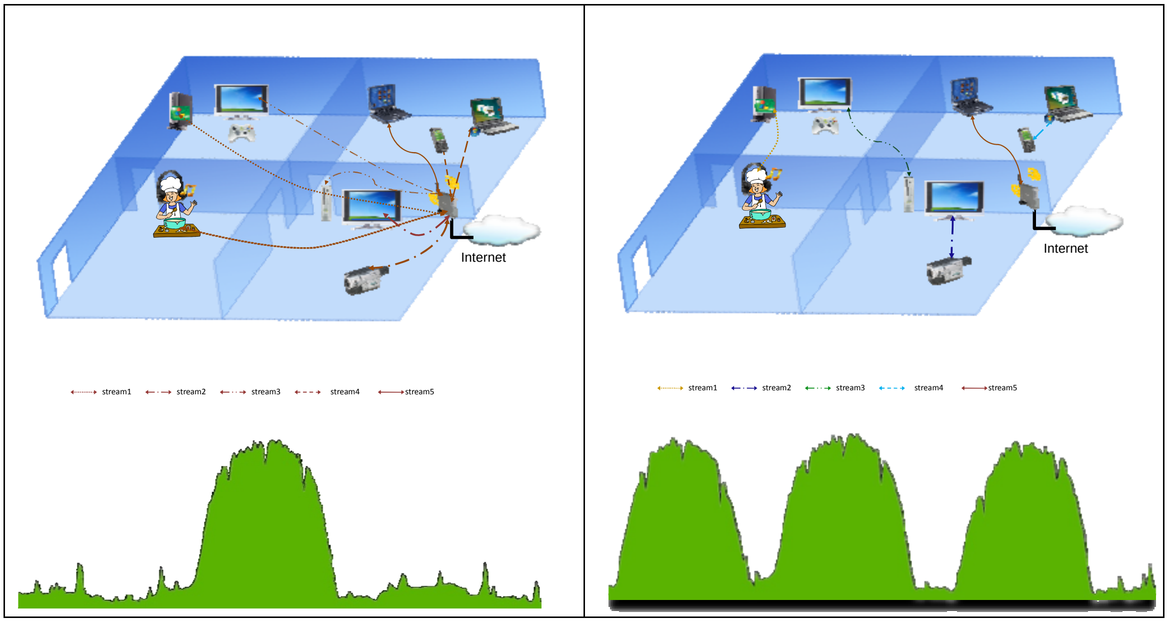


Figure 2: Access-point network (left) and peer-to-peer network (right) along with the associated improvement of the spectrum usage [12].

As an example, the “multi-radio home scenario” in the ARAGORN project [12] describes a vision for the home of the future where residents are able to access a range of devices and services (e.g., media servers, PDAs and wireless printers, DVD players, home security cameras and game consoles and even coffee machines and fridges). Figure 2 illustrates this scenario. With a current access-point-type home network based on, for instance, IEEE 802.11 technology, many problems may occur that may be suitably avoided when a cognitive system based on peer-to-peer communication is deployed.

When communication via the access point is avoided, an immediate result is a doubling of the spectral efficiency, but beyond this obvious advantage, a cognitive approach would result in more benefits. Available spectral resources can be used more efficiently, interference can be adaptively avoided, resource utilization can be optimized to the required quality-of-service, etc.

2.3 *Opportunistic Scenarios*

This class of scenarios is based on the notion of *Primary* Users (PU) and *Secondary* Users (SU) of spectrum. Here, primary users are those that own licenses for dedicated parts of the spectrum. Secondary users are those who, without license but under a distinct regulation regime, are allowed to access the spectrum licensed to the primary users. Typically, this distinct regulation regime is based on the secondary system’s capability to use the relevant spectrum bands without causing interference to the primary users. This is precisely what has been termed DSA before.

Users of a secondary cognitive radio system dynamically access the spectrum either as an *underlay* system or as an *overlay* system. Some authors also add a third category called *interweave* systems. In an underlay system the secondary user is allowed to transmit provided that a constraint on the total interference power experienced by the primary is satisfied. Technologies such as Ultra-Wideband (UWB) are often proposed as a communication method of choice for the secondary users in this context. Authors using division into two categories (underlay and overlay) define an overlay system by requiring that the secondary users continuous sense the spectrum to assess whether the primary user is using it at given time, place and frequency. If no primary user is detected, secondary user can transmit. Other authors use the term interweave system for such technologies, and say that an overlay system instead is characterised by the fact that it enables simultaneous use of the spectrum by primary and secondary user simultaneously using, for example, cooperative relaying and coding techniques. The term *collaborative* system could also be used.

Scenarios that belong to this group have been given by several organizations and projects, such as ETSI RRS [6], SCC-41 [7], ITU [8], IEEE 802.22 [9], the SENDORA project [11], and the SDR-Forum [13]. Many of these mirror those of the license-exempt bands, with the natural distinction that in addition to network optimization tasks CRs have to carry out one of the dynamic spectrum access functions discussed above. Common scenarios include networks of ad hoc type operating in licensed bands in opportunistic manner, and the closely related tactical military networks. For civilian use emergency networks have also often been mentioned as a key application scenario, in which DSA and network optimization and self-organization are required to cope with high degree of dynamics and hostile propagation conditions in the network. Finally, cognitive home networks operating in DSA fashion form a major potential application area, especially related to reuse of frequencies originally assigned to broadcasters. Such a scenario is of course closely related to the "multi-radio home scenario" discussed above.

A first solid example of a practical scenario is that of the IEEE 802.22 standard, illustrated in Figure 3. This standard aims at "using cognitive radio techniques to allow sharing of geographically unused spectrum allocated to the TV broadcast service, on a non-interfering basis, to bring broadband access to hard-to-reach low-population-density areas typical of rural environments" [25]. A base station according to this broadband access standard can serve up to 255 fixed units (homes) within a rural area of typically 25 km in radius (up to 100 km). Again, this will be the basis for all DSA reporting in the document.

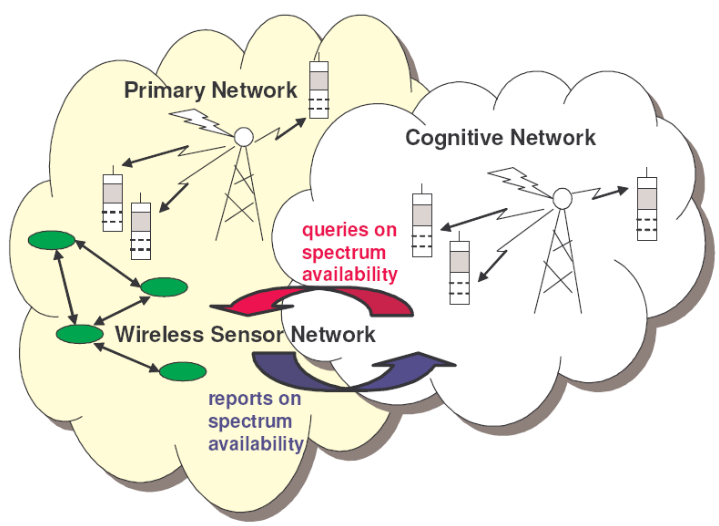


Figure 3: Conceptual illustration of the coexistence of
a (secondary) cognitive network and a (primary) licensed network [11].

A second example is public-safety communications systems described in [13]. In that report, the 7 July bombing of the London underground is analyzed in order to "envision how evolving cognitive (radio) technology could enhance the ability of responders in the future to communicate more effectively and efficiently than available technology allowed". Among the four examples of how cognitive technology could be used in such situations, the second (dynamic access of additional spectrum) is of particular value in our context. This usage case identifies communications difficulties resulting from the sheer volume of calls on the voice communications network (mobile phones). Dynamic spectrum access could, according to [13], be a solution in such a scenario of capacity-limitations. This then involves the employment of spectrum bands that are normally not used by the mobile phone system. One way to identify un-used or under-used spectrum is to monitor the spectrum use in frequencies not licensed to the network and to reconfigure the network and the subscriber equipment to use that spectrum (in emergency situations only).

2.4 *Other Possible Scenarios*

Here two other possible scenarios, namely *cognitive femtocells and vehicular CR networks* are described for a potential CR network deployment and usage.

2.4.1 Cognitive Femtocells

Femtocells [26], also known as home base stations, are consumer-installed, low-power, short-range access points used for increased indoor cellular coverage to provide high data rates for cellular users. Femtocells are usually connected with the macrocell (BS) through a broadband wired connection such as cable or DSL line, or through a wireless back haul link. In cognitive femtocells, determining a spectrum sharing strategy for a femtocell to share the spectrum allocated to its corresponding macrocell is a crucial issue, whether on an orthogonal basis (where the femtocell and the macrocell share different sections of the allocated spectrum to the macrocell) or on a non-orthogonal basis (where the femtocell reuses the spectrum allocated to its macrocell). The obvious trade-off between these two strategies is increased cell capacity versus increased interference between the macrocell and femtocells, and among the different femtocells.

While the spectrum is licensed in traditional macrocell and femtocell deployment and the notion of primary and secondary users is not exactly applicable, cognitive femtocells may operate opportunistically within the macrocell allocated spectrum. By employing spectrum sensing on the macrocell spectrum band, femtocells can identify channels that are not being utilized by the macrocell at the moment and use these channels for their own transmissions, i.e. operating on a non-orthogonal spectrum basis with the macrocell and thus saving valuable spectrum resources. One might think that macrocells could inform the femtocells about the channels being used in their vicinity, but such a solution will introduce significant overhead to the macrocell, especially in view of the fact that femtocells are usually installed by the consumer and can be randomly placed, thus it might be necessary that interference coordination be performed in a decentralized fashion.

In this regard, the deployment of CR femtocells is a spectrally efficient way of utilizing the macrocell allocated spectrum. Cooperation between the different femtocells within a certain macrocell is vital for interference avoidance and efficient spectrum sharing. Since the transmission range of CR femtocells is limited, cooperative relays for self-coexistence of multiple CR femtocells is required for effective cooperative spectrum sharing. For example, two nearby femtocells might observe different channel availability in a macrocell allocated spectrum. In order for these two femtocells to optimally utilize these vacant channels, they need to use an interference-aware resource allocation scheme in order to avoid interference to each other and to the macrocell. They can also rely on cooperative relays to further improve spectrum utilization with other femtocells outside their transmission range.

2.4.2 Vehicular Cognitive Radio Networks

Vehicular communication networks have received wide attention in the past decade as a way to support interesting applications such as driving safety, accident avoidance, and in-car infotainment, among others. Here we consider vehicular CR networks, where vehicle-to-vehicle (V2V) and vehicle-to-roadside (V2R) infrastructure communication is carried out opportunistically over some vacant spectrum ("white-space"). Figure 4 depicts a typical deployment of such networks in a TV band white-space. The white-space in the UHF band made available due to the recent Digital Television (DTV) transition is of special importance for such an application due to the favourable propagation characteristics of UHF frequencies as compared to the 5.9 GHz band currently allocated for vehicular communications under the Dedicated Short Range Communication (DSRC) framework. The fact that this TV band occupancy changes from one geographic location to another has an added benefit that guarantees the continuous availability of vacant spectrum thus maintaining network connectivity, especially for vehicles moving along freeway corridors. Moreover, interference to co-existing PUs can be avoided by implementing low power transmission, which also conforms with the FCC restrictions on CR portable/personal devices to limit their transmit power to levels below 100 mW .

Due to high mobility of vehicles, vehicular CR networks face more challenges compared to fixed CR networks. Specifically, fast cooperative spectrum sensing schemes are needed as a result of the rapidly changing spectrum occupancy and vehicle mobility. As vehicles may be blocked by buildings or mountains, the cooperative sensing scheme is required to reduce the sensing delay and improve PU detection in such correlated shadowing environment. In addition to the fast wideband cooperative spectrum sensing, the frequency agile non-orthogonal transmission technique is used to both satisfy bandwidth requirements and adapt to the rapidly changing environment. As shown in Figure 4, vehicles and roadside infrastructure are used as cooperative relays for spectrum sharing when spectrum heterogeneity is observed. A resource allocation scheme is needed for vehicles to optimally share rapid switching channels as the result of high mobility. In addition, fast cooperative spectrum sensing and sharing algorithms for high mobility vehicular CR networks are required to reduce the aggregate interference and to detect PU activity in vehicular CR networks operating in the UHF white-space as PU receivers of the mobile ATSC DTV system known as ATSC-M/H.

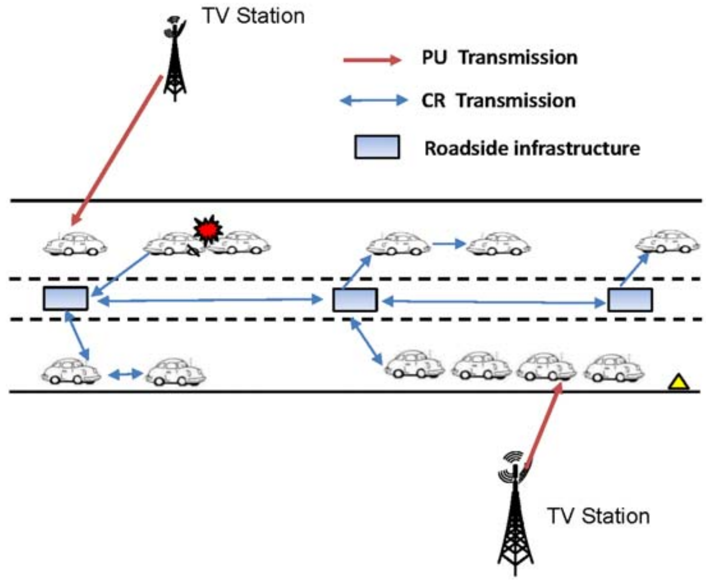


Figure 4: Typical deployment of vehicular CR networks in TV band whitespace.

3 Cognitive Radios, Enabling Technologies and Applications in DSA

3.1 *Cognitive Radios in General*

As mentioned, the original definition of a cognitive radio given by Mitola is that of a smart, context-sensitive radio, capable of learning and adapting across the protocol stack under varying environmental conditions [41]. The operation of a cognitive radio is typically assumed to follow the cognitive cycle depicted in Figure 5, also originally defined by Mitola. Any CR following this cycle gathers observations from the outside world through different types of sensors, which is then followed by orientation, planning of possible courses of actions, making decisions between the different choices, and then carrying out the decisions made. While this "outer loop" is processed, the CR also learns of the outcomes of its decisions and sensory inputs from the outside world and keeps updating its world model, thus representing its perception as to how the environment and its relations to other radios would be affected by the different actions undertaken. The cognitive cycle also features a number of provisions for carrying out urgent decisions and actions, should the sensory inputs and the world model indicate that such quick actions are required.

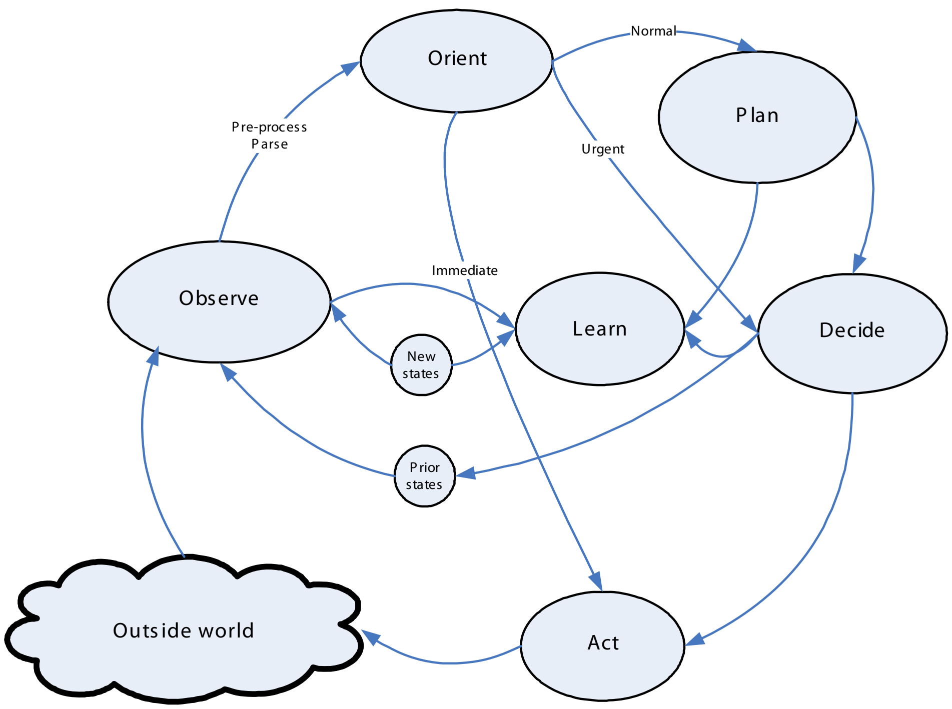


Figure 5: The cognitive cycle (adapted from [41]).

Clearly this original definition of a cognitive radio is very general, applicable to a vast number of scenarios, some of which we have mentioned in the previous Section. In Mitola's original work the observations, for example, were not specifically focused on radio spectrum only but also included other sensory inputs such as sound, images from cameras, speech recognition and geo-location. Similarly, planning and actions were not limited to the radio domain, but rather encompassing the entire protocol stack. Thus, general cognitive radio should be seen as an adaptive, self-organizing architecture for holistic resource management in wireless networks, an entity capable of adjusting its own behaviour through learning. This is also the viewpoint adopted in the FARAMIR project.

The support of cognitive cycle requires a number of different enabling technologies, and we shall now give a short list of the key enablers considered in the project, which will be further detailed in the following Sections. We begin from the "observe" state. A cognitive radio can observe a number of different aspects of its environment. The most commonly cited example is the classical radio environmental information obtained through some kind of *spectrum sensor*. Typically a spectrum sensor would measure characteristics such as total received power over a range of frequencies, or presence of signals transmitted by particular technologies or certain families of digital modulation schemes. This spectrum sensor (or analyzer) could also be implemented either on an individual CR through a hardware component, or can be based on cooperation between several CRs in the neighborhood. The observations could also be done by means of explicit communication between different radios, for example, some transmitters explicitly sending control information on the frequencies being used.

As already mentioned above, cognitive radios can in general make observations regarding not only spectrum, but other contextual information as well. Geo-location information in terms of either absolute coordinates or relative positions is a common example, with direct application in various radio-resource management problems. Any localization or tracking framework can be used as source of such data, as could be satellite-based systems such as GPS, or short-range localization methods based on wireless communications. Further types of sensors that can provide observations to CRs include audio/visual ones, present on numerous platforms, as well as accelerometers and gyroscopes that can be used to assess, for example, imminent changes in location and thus in propagation environment.

The orientation stage is related to processing of the information obtained from the different sensors, and integrating that with any prior knowledge in order to update the estimate of the state of the system and its environment. Depending on the diversity of the sensing information and prior knowledge available, numerous different state estimation and learning mechanisms can be used in the orientation state. For example, further processing of information obtained through spectrum sensors can be fused with location information to make logical conclusions whether certain transmitters are active or not. Depending on the change in state, the CR shifts either to the planning stat, or, in case urgent reaction is required, to the decision state. The key difference between these two states is typically the level of real-time performance the associated algorithms are needed to exhibit. For example, appearance of a new client in a cognitive femtocell network could trigger an urgent connection admission control and resource assignment routine, whereas in planning the state parameters of power control algorithms, this could be adjusted in an outer control loop at a more relaxed pace. In any event, typically all the radio resource management algorithms in realizable cognitive radio systems and cognitive wireless networks would be expected to reside in these two states.

Following the decision making state, the CR should potentially act according to the decisions made. Actions here would typically relate to change in any of the tunable parameters across the entire protocol stack, including selection of protocols to be used, and actual links or end-to-end connections established to other nodes. In case the CR is implemented on a software-defined radio platform, actions could also include extensive reconfiguration of the waveform used.

Finally, at the centre of the cognitive cycle is the learning state. Here, the cognitive radio or a cognitive wireless network updates the different models it has constructed on the environment, on the properties of other radios, and on the dynamics of its own state. The key focus in FARAMIR regarding the learning state is the storage and processing of this environmental and state information. As discussed in the Introduction, Radio Environment Maps will form the common framework for storing, processing and exchanging such information. The main research issues and challenges related to REMs will be discussed at length in Section 4, thus we shall not enter into that discussion here. Algorithms needed for the learning process include statistical analysis and long-term modeling of the environment based on sensor readings, as well as on responses in those readings to actions chosen to be carried out in the decision stage. Techniques and theory such as machine learning also play a key role here.

The above discussion on CRs and enabling technologies has thus far been conducted on a general level, applicable to a wide variety of scenarios and autonomous network optimization tasks, and without explicit focus or specialization on spectrum management problems. One of the key areas in which cognitive radio concepts have attracted considerable interest is precisely management of radio spectrum, and more specifically the opportunistic spectrum use of unused licensed frequency bands. For example, DARPA's NeXt Generation (xG) program has aimed to implement policy-based intelligent radios [34]-[38] precisely in this fashion. Due to its prevalence in the literature, we shall now briefly discuss how cognitive radio principles are typically applied for opportunistic access. Nevertheless, we once more note that even though opportunistic spectrum use and dynamic spectrum access are important topics for the project, they are by far *not* the sole focus of FARAMIR.

3.2 *Cognitive Radios for Dynamic Spectrum Access*

The CR technology in the context of DSA will enable the users to (1) determine which portion of the spectrum is available and detect the presence of licensed users when a user operates in a licensed band (spectrum sensing), (2) select the best available channel (spectrum decision), (3) coordinate access to this channel with other users (spectrum sharing), and (4) vacate the channel when a licensed user is detected (spectrum mobility). Focussing on these functions results in a simplified version of the full cognitive cycle shown in Figure 6 below.

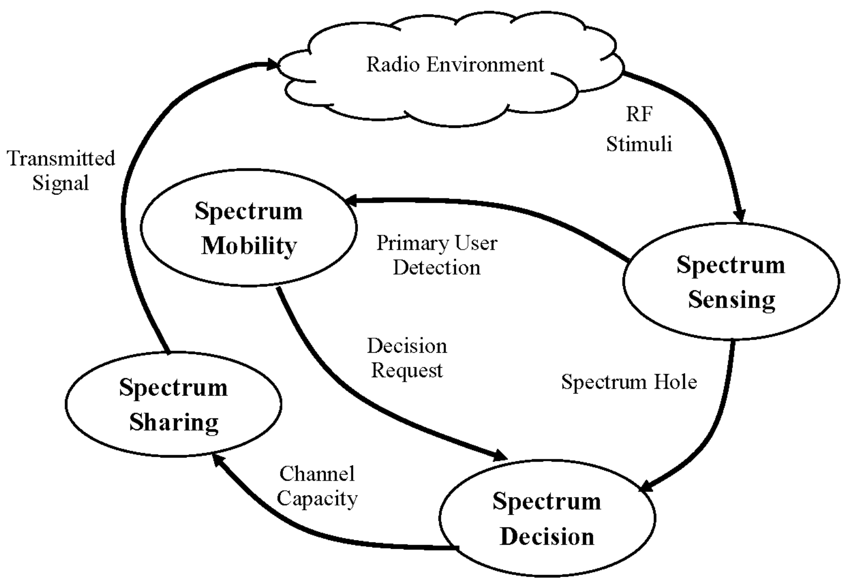


Figure 6: Specialization of the cognitive cycle to the dynamic spectrum access case [36].

The states in this simplified cognitive cycle defining the spectrum management process consists of four major steps [37]:

1. *Spectrum Sensing:* A CR user can only allocate an unused portion of the spectrum. Therefore, the CR user should monitor the available spectrum bands, capture their information, and then detect the spectrum holes.

2. *Spectrum Decision:* Based on the spectrum availability, CR users can allocate a channel. This allocation not only depends on spectrum availability, but it is also determined based on internal (and possibly external) policies.

3. *Spectrum Sharing:* Since there may be multiple CR users trying to access the spectrum, CR

network access should be coordinated in order to prevent multiple users colliding in overlapping portions of the spectrum.

4. *Spectrum Mobility:* CR users are regarded as "visitors" to the spectrum. Hence, if the specific portion of the spectrum in use is required by a primary user, the communication needs to be continued in another vacant portion of the spectrum.

However, compared to the full cognitive cycle, the loop is missing a few important components. One is an overarching goal, which should feed in from outside the loop and guide the orientation and decision components by providing a context in which to make a decision. Another missing component is a learning module, which prevents mistakes from previous iterations from being made on future iterations.

The spectrum management framework for CR network communication is illustrated in Figure 7. It is evident from the significant number of interactions that the spectrum management functions necessitate a cross-layer design approach. We shall provide a detailed review of the different spectrum sharing approaches for cognitive radio, both for DSA and general applications in Section 6.

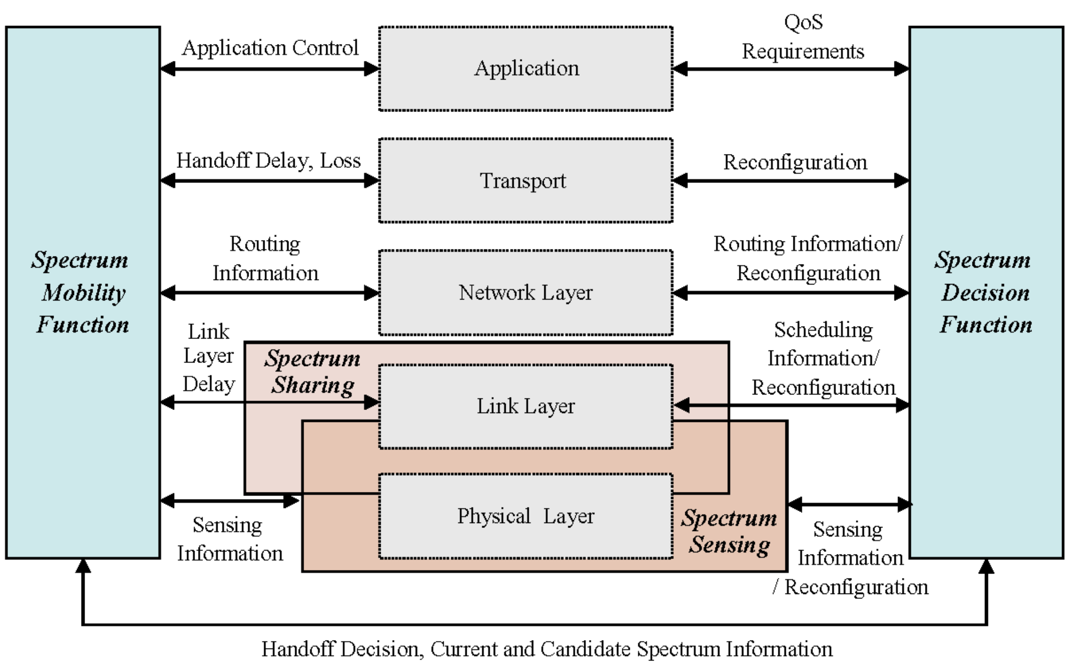


Figure 7: Spectrum management framework for cognitive radio networks (from [36]).

Once a radio supports the capability to select the best available channel, the next challenge is to make the network protocols adaptive to the available spectrum. Hence, new functionalities are required in a CR network to support this adaptivity and to enable spectrum-aware communication protocols. The components of the typical CR network architecture when applied to DSA, as shown in Figure 8, can be classified in two groups as the *primary network* and the *CR network*. *Primary network* is referred to as the legacy network that has an exclusive right to a certain spectrum band. Examples include the common cellular and TV broadcast networks. On the contrary, *CR network* does not have a license to operate in the desired band. Hence, the spectrum access is allowed only in an opportunistic manner.

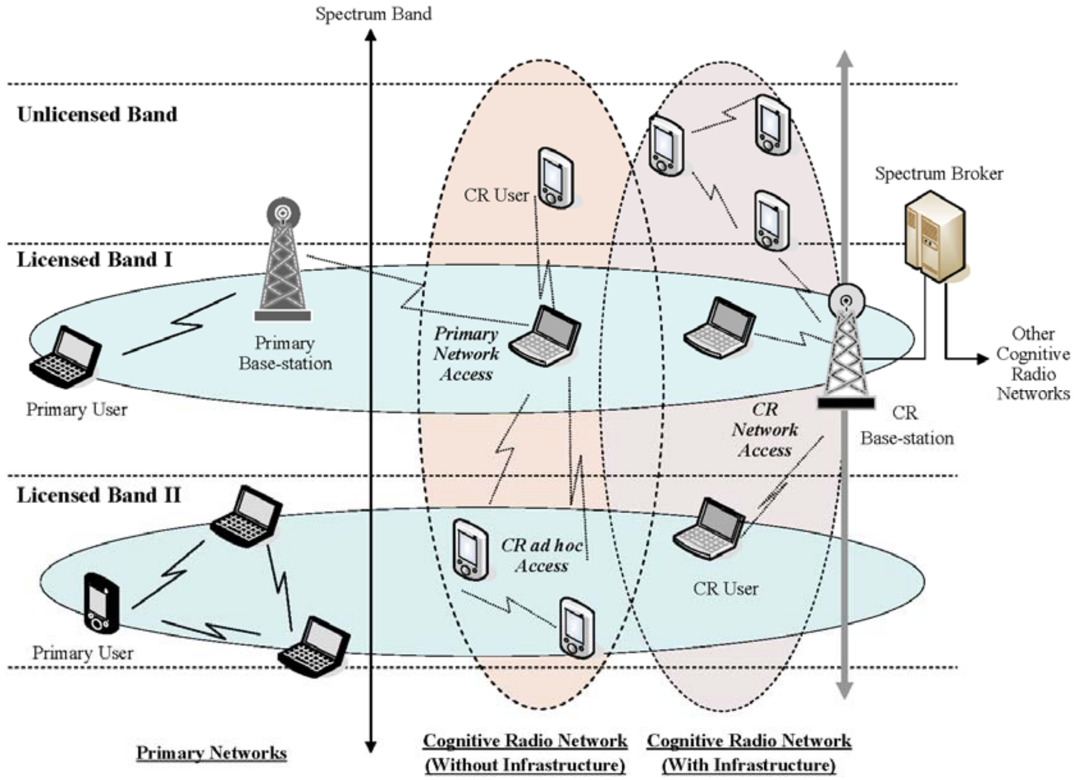


Figure 8: CR network architecture for dynamic spectrum access applications (from [36]).

The followings are the basic components of primary networks [38]:

- *Primary user:* Primary user (or licensed user) has a license to operate in a certain spectrum band. This access can only be controlled by the primary base-station and should not be affected by the operations of any other unlicensed users. Primary users do not need any modification or additional functions for coexistence with CR base-stations and CR users.

- *Primary base-station:* Primary base-station (or licensed base-station) is a fixed infrastructure network component which has a spectrum license such as base station transceiver system (BTS) in a cellular system. In principle, the primary base-station does not have any CR capability for sharing spectrum with CR users. However, the primary base-station may be requested to have both legacy and CR protocols for the *primary network access* of CR users, which is explained below.

The basic elements of the CR network are defined as follows [38]:

- *CR user:* CR user (or unlicensed user, cognitive radio user, secondary user) has no spectrum license. Hence, additional functionalities are required to share the licensed spectrum band.

- *CR base-station:* CR base-station (or unlicensed base-station, secondary base-station) is a fixed infrastructure component with CR capabilities. CR base-station provides single hop connection to CR users without spectrum access license. Through this connection, a CR user can access other networks.

- *Spectrum Broker:* Spectrum broker (or scheduling server) is a central network entity that plays a role in sharing the spectrum resources among different CR networks. Spectrum broker can be connected to each network and can serve as a spectrum information manager to enable coexistence of multiple CR networks [49], [50], [51].

According to the reference architecture shown in Figure 8, various functionalities are required to support the heterogeneity in CR networks. In the following subsections, we give an overview on CR network applications and architectures with respect to different types of heterogeneity.

3.2.1 Network Heterogeneity

The existing architectures can be classified in:

- *Infrastructure-based (Centralized) Network:* In this architecture, some powerful entity such as base-station exerts ownership and control over the nodes within its range. The observations and analysis performed by each CR user feeds to the central CR base-station so that decisions can be made by the base-station on how to avoid interfering with primary networks.

- *Ad-hoc (Distributed) Network:* CR ad hoc networks (CRAHNs) [36] do not have a central network entity such as a base-station or an access point. Thus, each CR user should have all functionalities for dynamic spectrum access. In this architecture, these functionalities are executed either in a non-cooperative or in a cooperative manner.

- *Mesh Network:* Wireless mesh networks are emerging as a cost-effective technology for providing broadband connectivity [52]. However, as the network density increases and the applications require higher throughput, mesh networks require higher capacity to meet the requirements of the applications. Since the cognitive radio technology enables the access to larger amount of spectrum, CR networks can be used for mesh networks that will be deployed in dense urban areas with the possibility of significant contention [53]. The components of cognitive mesh networks are as follows:

    - *Cognitive Mesh Router:* It serves as the Access Point supporting several users in a residential setting or along the road.
    - *Cognitive Mesh Client:* MCs are free to either associate themselves with a MR in a cluster, or form their own ad-hoc network.
    - *Gateway:* The mesh routers can be connected to the Internet or other wireless/wired networks such as cellular and WiFi networks.

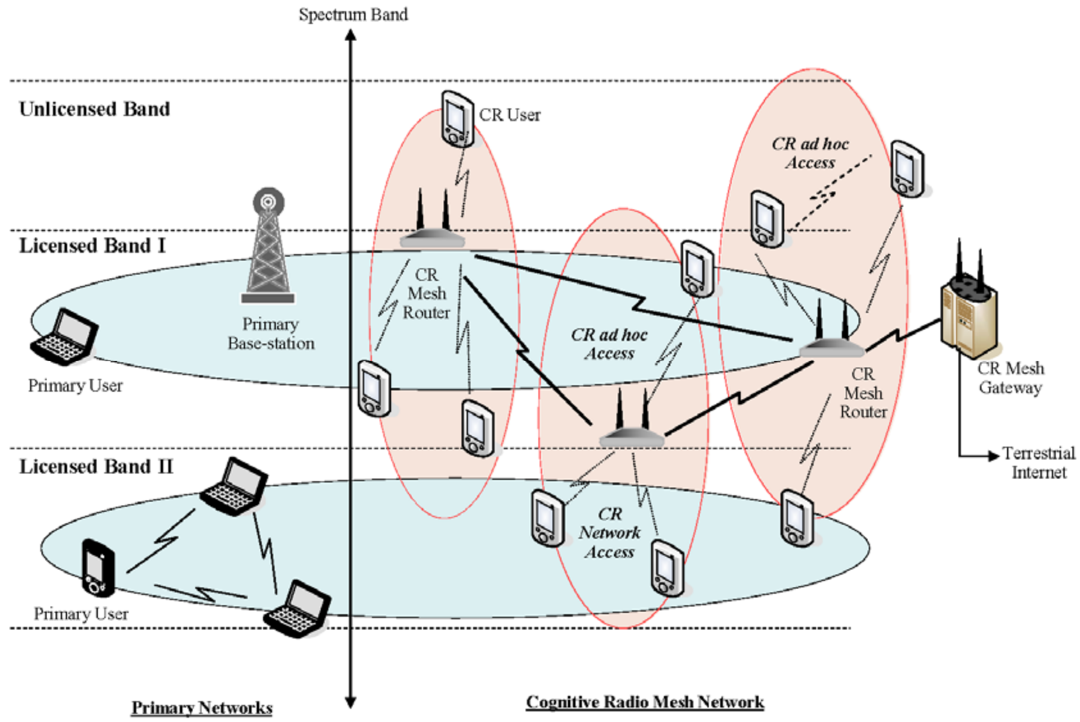


Figure 9: CR mesh network architectures in a dynamic spectrum access scenario.

3.2.2 Access Heterogeneity

The reference CR network architecture is shown in Figure 9, which consists of different types of networks: a primary network, an infrastructure based CR network, and an ad-hoc CR network. CR networks are operated under the mixed spectrum environment that consists of both licensed and unlicensed bands. Also, CR users can either communicate with each other in a multihop manner or access the base-station. Thus, in CR networks, there are three different access types as explained next:

- *CR Network Access:* CR users can access their own CR base-station both on licensed and unlicensed spectrum bands. Since all interactions occur inside the CR network, their spectrum sharing policy can be independent of that of the primary network.

- *CR Ad-hoc Access:* CR users can communicate with other CR users through ad-hoc connection on both licensed and unlicensed spectrum bands.

- *Primary Network Access:* CR users can also access the primary base-station through the licensed band. Unlike other access types, CR users need an adaptive MAC protocol, which enables roaming over the multiple primary networks with different access technologies.

3.2.3 Spectrum Heterogeneity

As explained before, CR network can operate in both licensed and unlicensed bands. Hence, the functionalities required for CR networks vary according to whether the spectrum is licensed or unlicensed. We classify the CR network operations as:

- *CR Network on Licensed Band:* There exist temporally unused spectrum holes in the licensed spectrum band. Hence, CR networks can be deployed to exploit these spectrum holes through cognitive communication techniques. This architecture is depicted in Figure 10, where the CR network coexists with the primary network at the same location and on the same spectrum band.

There are various challenges for CR networks on licensed band due to the existence of the primary users. Although the main purpose of the CR network is to determine the best available spectrum, the interference avoidance with primary users is the most important issue in this architecture. Furthermore, if primary users appear in the spectrum band occupied by CR users, CR users should vacate the current spectrum band and move to the new available spectrum immediately, called *spectrum handoff*.

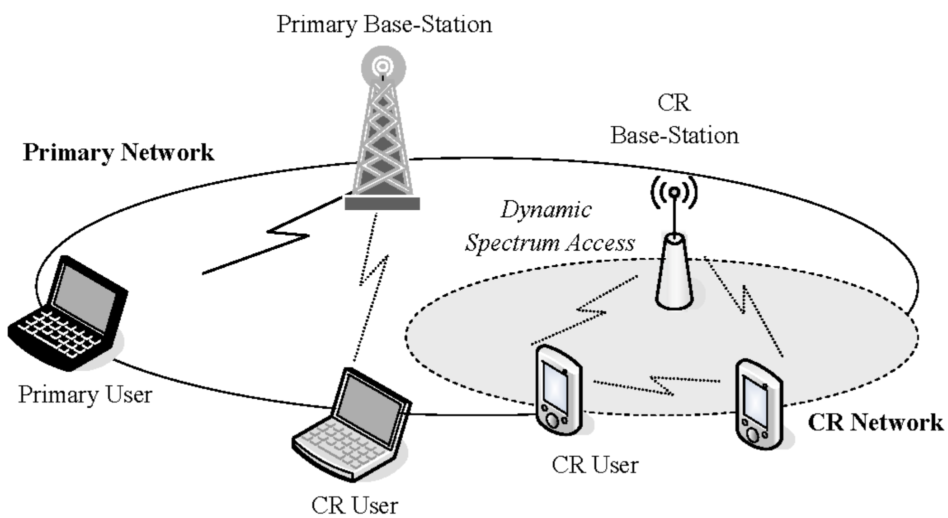


Figure 10: CR network on licensed band with dynamic spectrum access (from [36]).

- *CR Network on Unlicensed Band:* Open spectrum policy that began in the industrial scientific and medical (ISM) band has caused an impressive variety of important technologies and innovative uses. However, due to the interference among multiple heterogeneous networks, the spectrum efficiency of ISM band is decreasing. CR networks can be designed for operation on unlicensed bands such that the efficiency is improved in this portion of the spectrum.

The *CR network on unlicensed band* architecture is illustrated in Figure 11. Since there are no license holders, all network entities have the same right to access the spectrum bands. Multiple CR networks coexist in the same area and communicate using the same portion of the spectrum. Intelligent spectrum sharing algorithms can improve the efficiency of spectrum usage and support high QoS. In this architecture, CR users focus on detecting the transmissions of other CR users. Unlike the licensed band operations, the spectrum handoff is not triggered by the appearance of other primary users. However, since all CR users have the same right to access the spectrum, CR users should compete with each other for the same unlicensed band. Thus, sophisticated spectrum sharing methods among CR users are required in this architecture. If multiple CR network operators reside in the same unlicensed band, fair spectrum sharing among these networks is also required.

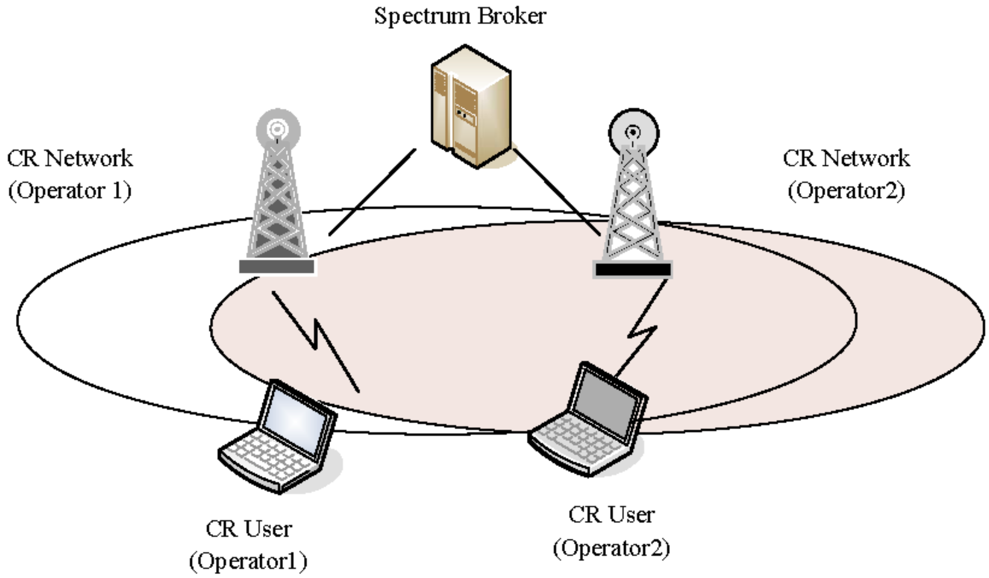


Figure 11: CR network on unlicensed band (from [36]).

4 Radio Environment Maps

It is clear from the above discussion that both the spectrum sensing tasks as well as the other resource-management decisions that cognitive radios have to face are highly dependent on the state of the environment (radio-emission state, topological state, etc.). Much of the work on cognitive radios has been based on making inferences about that environmental state solely at the time of decision making, especially when focussing on dynamic spectrum access (or anything else of highly dynamic nature). However, it has also become clear that any additional and temporally consistent (i.e., long-term) knowledge of the environment can be used to significantly improve the accuracy and performance of the decision-making process. Such information includes "typical" behaviour of other transmitters in the area as well as propagation conditions, just to name a few examples, usually assumed to be stored in a database-like system, locally or globally. The term Radio Environment Map (REM) is typically used to characterize such a database, which implies that the information regarding the radio environment is critical to have. The key to the REM design is to decide what type of information must be stored and how this would be available to the various radios (CR or otherwise).

The REM, supported by distributed CR nodes and/or network infrastructure, is envisioned as the large-scale navigator for CRs. It provides cognitive services to the associated internal networks as well as a useful awareness of external networks such as non-cognitive legacy systems. REM covers (but is not limited to) multi-domain environmental information such as geographical features, available services, spectral regulations, location of various entities of interest (radios, reflectors, obstacles) plus radio-equipment capability profiles, relevant policies and past experiences (Figure 12). The REM information can be updated with observations from CR nodes and disseminated throughout CR networks [54]-[56].

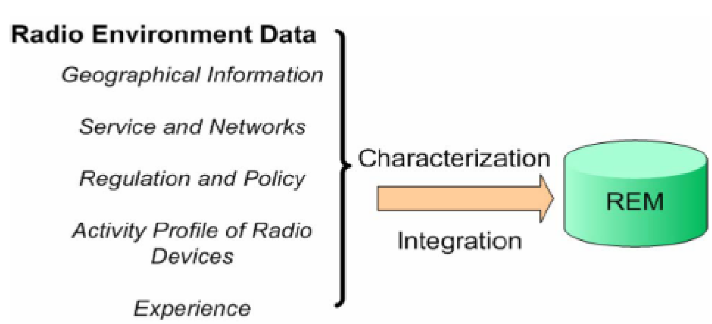


Figure 12: REM characterizes the radio scenario and offers network support and prior knowledge (from [124]).

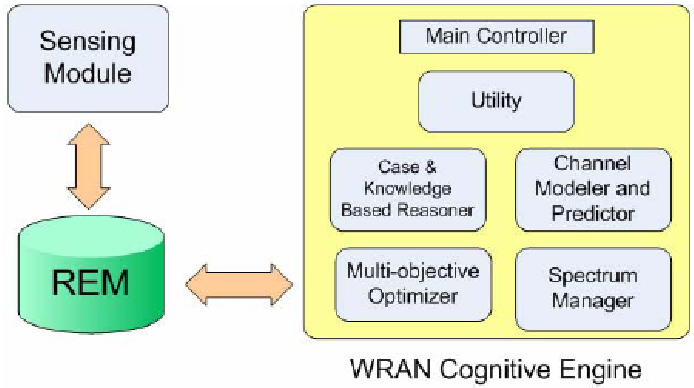


Figure 13: Architectural diagram of REM-based CE for 802.22 WRAN BS (from [124]).

Different REM architectures could be classified as either *global* or *local* REMs, depending on the origin, extent and the purpose of the information stored, and the scope this information can be accessed from. A global REM would usually be implemented at least partially as a network back-end system whereas a local REM would usually reside within the network of cognitive radios. The local and the global REMs could also be integrated into some common frame and could exchange data periodically in order to keep the stored information current (Figure 14). REM information (either global or local) could be disseminated into the network using either via (a) dedicated control channel or (b) sharing a traffic channel.

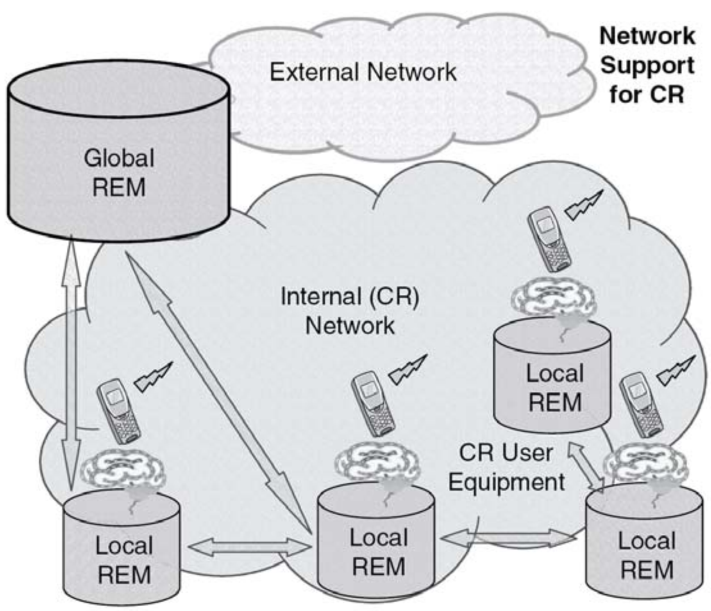


Figure 14: Local and global REMs [54].

It stands to reason that cognitive wireless networks would benefit the most from an integrated architecture including both global and local REMs, i.e., by combining information from these two databases. The global REM, especially if implemented in back-end, could be used to store larger amounts of data as well as to carry out more intensive computations, whereas local REMs would improve responsiveness and decrease latency. Some of the example usage cases illustrating these benefits are the following:

- The interference range of a CR in most cases is larger than the sensing range of its radio. Thus the global REM could be used from the CR to "see" far beyond its sensing range and improve environmental characterization. In [61] it is shown that the global REM information about the positions of primary users improved the CR performance by about 2-10 dB as compared to the case that only the local REM was used.
- Local REMs are restricted to limited time-scale measurements in comparison with the global REMs that might contain measurements for larger time scales (ex. days, weeks, months). This global REM recording of activities could be used from CRs as a prediction of primary users' activities in the near future.
- Local REM information, stored in the various CR nodes, could be exploited from the global REM database. Actually, by combining all these measurements the global REM can infer the over time changes in the environment.

4.1 *Information stored in REMs*

There are numerous different types of information that the REMs could store. The simplest examples considered in the standards, such as IEEE 802.22, are transmitter locations and explicit protection zones around them. Also localization information of cognitive radios themselves are important both for assessing their relations with the protection zones, and for more general policy issues. However, for most resource-management and channel-access decisions, many other types of information could be relevant. Radio-propagation-environment information is one of the most important ones. The environment ("channel") is *the* determining factor for radio communications as it attenuates all wireless signals that travel through it in complex ways. Various models are commonly used to describe in a qualitative and quantitative manner the effects that the environment has on radio communications. Some of the most common parameters that the radio propagation models use are:

- Street width and building height (used in, for example, the Walfisch-Ikegami propagation model)
- Weather conditions
- Location and height of obstacles (e.g. building floor number is used to calculate the building penetration loss)
- Vegetation and tree heights (used in, for example Weissberger's model is used to estimate the path loss due to the presence of trees)
- Antenna heights of the base stations (used by most propagation models such as the Okumura-Hata model)
- Area type such as urban, sub-urban, highway, open rural, indoor, office, airport, etc.

Another type of information the REMs could store is the presence or absence of wireless services; this is something that differs greatly from an area to another. For example, radio broadcasts are usually found in areas where the population density is high. Thus, such services are usually present in urban or suburban areas and not densely present in open rural areas. CRs can exploit the absence of such services in an opportunistic spectrum-reuse manner, as mentioned in the above Section on scenarios. Spectral regulations are also an example of heavily geographically-dependent information that changes slowly and thus could easily be stored in a REM.

Information about the layout ("topology") of primary and secondary networks would also be useful in resource management and DSA-related decisions. In the REM case, "topology" is typically used to describe the location and the connectivity of the nodes. For several applications in the cognitive radio domain knowledge of individual node locations is not strictly speaking necessary.

Instead, *statistical description* of locations can be used as well. For example, interference or total received power is typically dominated by contributions from few of the closest transmitters. Thus, distributions of the distances to the nearest neighbours can already be used as a basis for a number of algorithms. Such distributions estimated from location data are examples of *spatial statistics*, methods to describe the *structure* of locations without enumerating all the individual coordinates.

In general, cccording to [57], three types of topological information can be stored in a REM:

- Raw location data, either known precisely or estimated using localization techniques.
- Statistics of measurements, such as the pair correlation function of the node locations [58].
- Models of the various phenomena arising in a network such as the formation of connections.

Statistics and models have the advantage that they describe the raw data with only few parameters (information-compression effect). In principle, this reduces the burden of storing large volumes and eases the calculation requirements for decision-making purposes. Finally, such statistics and models ease the burdening of the limited wireless resources as less information need be transferred between network nodes.

The activities of PUs can provide further insights into the radio environment. In [59] the authors show that the spectrum use is clustered in the frequency domain, which might prove valuable for making approximate predictions for opportunistic spectrum use. Although the individual user activities are obviously important in any decision-making process, there is no straightforward way of storing such information. Brute-force storage of raw measurement data is impractical as the volume increases very quickly. Ref [60] provides a partial answer to this problem by proving that spatial statistics and random fields can be used instead to model spectral maps, thus reducing the volume of needed and stored data.

4.2 *Challenges in applying REM data*

One of the key challenges in REM design and applications thereof is dealing with various imperfections inherent in the data and in accessing them. In the global REM case there is always a time period needed for this global REM information to be transmitted to the entire network. This time period is referred to as “dissemination delay”. This delay is due to several factors such as the time needed to acquire a channel for transmitting data, capacity limits of the information-relaying channel, or just finite buffers of nodes [61], [62]. Another issue is due to possible node mobility. CRs as well as PUs have the option to move towards any direction they wish. Thus, when a PU moves previous information concerning the primary user’s position will result in an improper transmit power adjustment. In references [61] and [62] the authors show that as the PU moves faster, the greater the SINR degradation becomes (Figure 15).

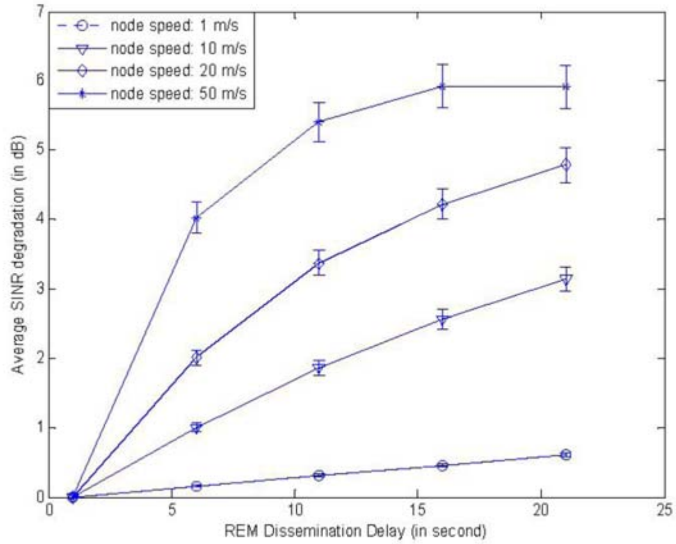


Figure 15: Averaged SINR degradation comparison under various PU moving speeds [61].

The sensing process itself also suffers from various limitations. Sensing with great accuracy is usually a complex and expensive feature. Therefore, practical sensors (either residing within the CR's or independently) must resort to coarser resolution bandwidth sensing which tends to misclassify spectrum usage. For instance, a coarse resolution of 300 KHz will misclassify white spaces of few tens of KHz. The sensing sweeping time must also be kept as short as possible for a good spectrum-usage assessment. This is in addition to the fact that the sensing process must stop when the CR transmits data to receivers that do not possess a separate sensor. Unfortunately, for an accurate REM, a very short sweeping time is needed which leads to huge amount of data (a volume hard to handle). So the necessary compromise between the sweeping time and the amount of data collected will further lead to imperfections in the REM information. The radio environment itself is also usually highly dynamic and therefore its parameters (such as shadowing or fading) fluctuate over time. In general the true benefits of employing REMs in different applications will also depend on both the quantity and the quality of the measurements. "Quantity" refers to how much information is needed while "quality" refers to what is the acceptable estimation error in the measurements. The requirements in measurement quantity and quality depend on the type of problem at hand. The quantity requirements could be expressed in terms of space or/and time resolution requirements. For example, in a TV station measurement scenario, the required space resolution would be to take measurements every few kilometres while in a commercial wireless network case the requirement would be to take measurements every few meters. Moreover, the time resolution requirements depend on what needs to be tracked; thus, this may vary from ms time scales to seconds. For an interesting discussion on such space-time models and metrics specifically focussing on spectrum sensing, see [63].

4.3 Examples of key application areas of Radio Environment Maps

When understood in the general perspective discussed above, REMs apply to a number of application areas beyond simple geo-location-based channel availability assessments. Few of the most promising ones are listed in the following.

Network initialization: REM databases could be used to reduce initialization time. This is the time period needed by a just-turned-on cognitive radio in order to gather radio information and to become aware of the radio environment. When a CR turns on, it could get fresh REM information or update an older version it might have. The REM information could be obtained from the closest neighbour or from a central "entity". This new version of the REM contains measurements of the past which are valuable for the CR as it must rely on the past to predict the future.

Spectrum sensing: This is a power- and time-consuming process. Usually a CR must search for empty/idle spectrum bands in a wide frequency range. The REM contents of spectrum usage could reduce the time and the power consumption of the spectrum sensing process. For example, previous REM experience that some frequency bands have very high spectrum occupancy could lead to excluding those zones from the sensing process.

Improving PU protection and detection: The CRs operate on the assumption that they will not interfere with PUs. So, secondary users need to deal with problems like the hidden node one. In the hidden node problem a secondary user interferes with the transmission of the PU as it cannot sense the presence of the latter. Even though cooperative spectrum sensing mechanisms are useful in minimizing the effects of this problem, still past experience (for instance, where a hidden node was located before) properly integrated into the REM could be used for improving the protection of the PUs. Furthermore, statistical analysis could be used on the REM data to derive patterns such as duty ratios, channel reputations and dynamics in duty cycle. This analysis is the first-step for the calculation of the possibility of causing interference to PUs. Also, detecting the PUs' existence is not always easy due to several factors such as receiver noise,) signal attenuation and multipath fading. REM information could improve the detection rate of PUs by adjusting the detection threshold. For example, if a CR is behind a building, then a REM-based approach can adjust the detection threshold to account for the extra losses due to building penetration loss. In [65] the author assumes that the probability of the PU transmission is known (as it can be calculated using data from REM). Thereafter the *a priori* probability of the PU transmission is applied to dynamically adjust the threshold of the energy-detector.

Resource management and network optimization: REM-based approaches could also be used for Radio Resource Management and Optimization applications. For example, in a femtocell-based cognitive radio scenario, the REM could use the information about the environment to reduce the interference or adjust the wireless emissions inside an apartment.

Performance evaluation and source of models: Performance of future CRs could be predicted only under the emulation of CRs in a more realistic virtual environment. An REM-based environment is the most promising candidate toward the realistic performance evaluation and testing of CRs. In a sense, REM databases could be used as inputs for virtual-radio-environment generation.

4.4 *Interference Cartography*

Interference/spectrum cartography as introduced in [66], [67] combines measurements performed by different network entities (mobile terminals, base stations, access points) with the geo-location information and applies simple and effective spatial interpolation techniques to achieve a map which indicates the level of interference experienced at each mesh over the area of interest. This is a concrete example of application of spatial statistics techniques to wireless communications as discussed also in [57], [60].

As stated in [67], since interference is the major actor in any wireless network operation, almost every network management scheme uses interference information to guarantee a satisfactory level of performance. Thus, interference information already exists in wireless networks through periodic and/or event-triggered measurement reports provided by different network entities. The concept of interference cartography aggregates the pieces of interference information measured by entities of several different wireless networks at a central unit, combines this aggregated information with geo-localization information, performs advanced signal processing techniques to render the information complete and reliable and finally updates the information to provide a viable picture of the environment for efficient detection, analysis and decision.

The idea of constructing a geo-localized information database presented in the Radio Environment Map is similar to the idea behind interference cartography. However, the classical vision of REM relies only on reported measurements in database construction whereas the proposed concept constructs the cartography from partial measurement data using advanced signal processing techniques, offering quality/reliability criteria and additional measurement request mechanisms to satisfy these quality/reliability criteria. To achieve a certain level of precision and reliability, large amounts of measurement data may be needed in constructing a cartography that relies only on reported measurements. It is clear that such large amounts of data are bound to create storage and dissemination problems in the network.

The challenge of such effort lies in finding pragmatic solutions for constructing, keeping and updating measurement databases combined with efficient signal processing techniques that achieve high levels of precision and reliability with the minimum proportion of measurement data.

A framework that describes the needed functionalities for such effort is described in [66]. A spatial interpolation method based on Krige's work [68] and on a simple spatial covariance model for the interference was proposed in [67]. A framework in which the correlation model is derived from measurements and applied to kriging was also introduced independently in [60]. Another interpolation method based on a predefined propagation model was introduced in [69], by constructing a basis expansion model of the PSD in space and time. By exploiting the sparsity induced by the adopted scenario (scarce distribution of active transmitters in the area of interest and narrow-band nature of transmit-PSDs relative to the broad swaths of usable spectrum) the proposed solution could also estimate, as a by-product, the localization of transmitting radios. An alternative to the last solution, also based on a PSD basis expansion model was given in [70], using splines for spatial interpolation. This solution does not require a spatial covariance model as in [67] or a propagation model as in [69]. Finally, in [71] spatial statistics techniques were applied to measurement data and simulations in order to find realistic parameterisations for correlation functions that can be used for spatial interpolation.

Similar approaches which estimate the interference temperature of an area by appropriately utilizing multiple measurements exist in the literature. In [39] the interference temperature was estimated by proper use of the SVD, whereas in [72] a separation of the contributing transmitting sources was also accomplished through the use of recent advances in the field of large dimensional random matrix theory.

The limited work in this new field combined with the potential advances promised in the context of cognitive radio constitute a good target research field for FARAMIR.

4.5 Conclusions and Roadmap for the Review

We have seen that REMs have a large number of potential application areas, depending on the considered scenario and the capabilities of that particular REM. Nevertheless, there is significant amount of research and design work that the project has to carry out during its lifetime to make REMs practical engineering reality for wireless networks. The diversity of applications and potential scenarios indicates that there will not be a single deployment architecture or REM design. Instead, there seems to be a requirement for supporting a variety of deployments, both in terms of REM storage, as well as both production and consumption of data from REMs. This calls for a flexible architecture in which key interfaces and data models are defined precisely, together with extension mechanisms for adding support for new types of information to be measured, stored and consumed. The actual internal implementation of the REM should be left open, however, since this provides flexibility in tailoring the implementation solutions for particular deployment scenarios. The project will nevertheless develop concrete prototype implementations of REM solutions in order to obtain experience on challenges and merits of different solutions.

The focus on the rest of this Deliverable is to review the state of the art of the various technical components pertaining to radio environment maps, as well as different mechanisms for enabling and implementing cognitive wireless networks. In the following Section, different spectrum sensing techniques will be discussed in detail since, in any scenario involving REMs, sensing provides one of the key sources of data. This is followed by a review of the different spectrum sharing and resource management solutions for CWN in Sections 6 and 7. In Section 8 different testbed implementations are discussed, as well as different measurement campaigns on spectrum use and various models for spectrum data derived as a result of those measurements. The latter form one of the most important types of information REMs could be used to store and construct, and thus are critical for the present review. The development of standards related to REMs and corresponding IPR issues are discussed in Section 9. Finally, in Section 10 we draw conclusions, especially commenting on the level of maturity of the different technologies encountered in the review, and corresponding need for further research work in the context of the project.

5 Spectrum Sensing

Radio-Environment Awareness (REA) is a general requirement in communication systems that includes special tasks like detection (sensing) and Position-Location Estimation (PLE) of radio-emission sources, the subsequent identification of their internal features (if such identification is needed), description of the spectral profile of a given frequency band as "perceived" (i.e., *potentially* measured or extrapolated) at a particular location in space/time, and so on. All these tasks are meant to help the creation, improvement and updating of Radio Environmental Maps (REM) which can then be applied to many applications and services such as improving the capacity of cellular and other co-existing networks, hand-overs between them for load-balancing and interference-avoidance purposes, the introduction of Dynamic Spectrum Allocation (DSA)-based services, emergency communication systems, GPS-denied PLE, and so on. The ability to accurately characterize the operational environment by identifying the presence of, classifying their constituent parts (waveforms, in particular), and locating RF emitters in spatial terms is of great importance to all these applications. Currently emerging cognitive radio systems and networks induce heavy requirements on REA for determining unused spectrum bands and utilize them in an efficient way [73].

A cognitive radio (CR) is designed to be aware of and sensitive to the changes in its surrounding, which makes spectrum sensing an important requirement for the realization of CR networks. Spectrum sensing enables CR users to exploit the unused spectrum portion adaptively to the radio environment. This capability is required in the following cases: (1) CR users find available spectrum holes over a wide frequency range for their transmission (out-of-band sensing), and (2) CR users monitor the spectrum band during the transmission and detect the presence of primary networks so as to avoid interference (in-band sensing). The following functionalities for spectrum sensing are discussed in the succeeding sections:

- Primary User (PU) detection: The CR user observes and analyzes its local radio environment. Based on these location observations of itself and its neighbours, CR users determine the presence of PU transmissions, and accordingly identify the current spectrum availability.

- Cooperation: The observed information in each CR user is exchanged with its neighbours so as to improve sensing accuracy.

- Sensing control: This function enables each CR user to perform its sensing operations adaptively to the dynamic radio environment. In addition, it coordinates the sensing operations of the CR users and its neighbours in a distributed manner, which prevents false alarms in cooperative sensing.

We distinguish here between *active* and *passive* REA. The active version allows cooperative interrogation of the various RF sources and seeks their willing engagement in completing the REA mission. When REA is performed in a passive manner, however, then it requires that many radio-waveform parameters (e.g., the occupied bandwidth, the embedded data rate and modulation type, possibly the bit-stream itself) and other related features (the transmission medium's characteristics, signal direction of arrival, Doppler shifts, etc.) must be identified quickly, efficiently and accurately *without the help of the emitting source [74].*

A total REA system should, at a minimum, contain the following parts:

- A front-end processing block which detects ("senses") the signals of interest (such as the PU) and provides coarse estimates of certain critical RF characteristics such as operating frequency, spectral occupancy, baud rate, noise level, Signal-to-Noise Ratio (SNR), etc.;
- A processor which provides finer estimates of operational environment characteristics (such as a

channel estimate) as well as high-quality estimates of spatial emitter characteristics, such as Angle-of-Arrival (AOA), Time-of-Arrival/Time-Difference-of-Arrival (TOA/TDOA), and Frequency-of-Arrival/Frequency-Difference-of-Arrival (FOA/FDOA), whenever the scenario permits such. We term them all or a subset thereof "XOA".

- A Geo-Location System (GLS) that combines all the above plus (possibly) GPS-aided platform location/orientation information in order to provide emitter position location as accurately as physically possible.
- An all-encompassing Radio Environmental Map (REM) system that receives all this relevant estimated information (plus, possibly, other database-related entries) for a final assessment on, and presentation of, the radio environment and its properties.

5.1 *PU Activity Models*

In order to describe the dynamic nature of CR networks, we need a new metric to capture the statistical behaviour of primary networks, called primary user (PU) activity. Since there is no guarantee that a spectrum band will be available during the entire communication of a CR user, the estimation of PU activity is a very crucial issue in spectrum decision.

Most of CR research assumes that PU activity is modelled by exponentially distributed inter-arrivals, [75]-[80]. In this model, the PU traffic can be modelled as a two state birth–death process with death rate α and birth rate β. An ON (Busy) state represents the period used by PUs and an OFF (Idle) state represents the unused period [81]. Since each user arrival is independent, each transition follows the Poisson arrival process. Thus, the length of ON and OFF periods are exponentially distributed. There are some efforts to model the PU activity in specific spectrum bands based on field experiments. In Annex II details on the On-Off model are provided. In [82], the characteristics of primary usage in cellular networks are presented based on the call records collected by network systems, instead of real measurement. This analysis shows that an exponential call arrival model is adequate to capture the PU activity while the duration of wireless voice calls does not follow an exponential distribution. Furthermore, it is shown that a simpler random walk can be used to describe the PU activity under high traffic load conditions.

In [83], a statistical traffic model of Wireless LANs based on a semi-Markov model is proposed to describe the temporal behaviour of wireless LANs. Through empirical studies, it is shown that a hyper-Erlang distribution of the busy duration provides the best fitness to both stationary UDP traffic and non-stationary HTTP traffic in Wireless LANs. However, the complexity of this distribution hinders its practical implementation in CR functions. The above approaches are fixed models based on offline measurements. Hence, they do not adequately capture the time varying nature of the PU activity. In addition, similar to the classical Poisson model, these approaches fail to capture the bursty and spiky characteristics of the monitored data [84], [85]. However, as mentioned in [82], accounting for the short term fluctuations is also important so that CR users can accurately detect more transmission opportunities.

In order to accurately track the changing PU activity a novel real-time based PU activity model for CR networks is developed in [86]. Here, the PU signal samples are first collected over a pre-determined duration. Then, the observed PU signals are clustered together, if they are greater than a threshold. Based on this clustering, the current PU arrival-departure rates can be estimated. The duration of collecting the signal samples, as well as the threshold for classifying the observed value as a legitimate PU signal are calculated in this work. However, this approach needs several PU signal samples collected at one centralized location. Thus, this needs to be extended for CR ad hoc networks (CRAHNs), so that each CR user may form individual clusters of the PU signals, based on their local observation, which can then be combined to give the complete PU activity model. Moreover, the additive white Gaussian noise (AWGN) channel model used in the proposed approach does not incorporate the effects of fading and shadowing, which can lower the accuracy of the PU activity prediction.

5.2 *PU Detection*

A cognitive radio is designed to be aware of and sensitive to the changes in its surrounding, which makes spectrum sensing an important requirement for the realization of CR networks. Spectrum sensing enables CR users to adapt to the radio environment by determining currently unused spectrum portions, so-called *spectrum holes* without causing interference to the primary network.

Generally, spectrum sensing techniques can be classified into three groups: (1) primary transmitter detection, (2) cooperative detection, (3) primary receiver detection, and (4) interference temperature management as shown in Figure 16. In the following sections, we describe these spectrum sensing methods for CR networks and discuss the open research topics in this area as described in the following.

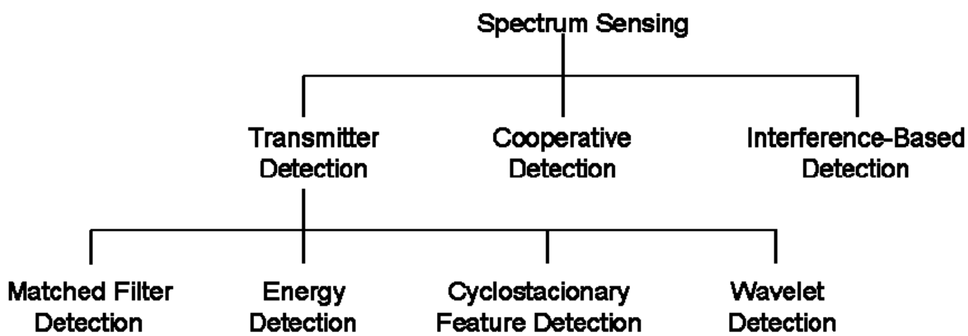


Figure 16: Classification of spectrum sensing techniques (from [36]).

5.2.1 Transmitter Detection (Non-Cooperative Detection)

Since CR users are usually assumed not to have any real-time interaction with the primary transmitters and receivers, they cannot know the exact information on current transmissions within the primary networks Thus, in transmitter detection, in order to distinguish between used and unused spectrum bands, CR users detect the signal from a primary transmitter through the only local observations of CR users, as shown in Figure 17. Thus, CR users should have the capability to determine if a signal from the primary transmitter is locally present in a certain spectrum. Basic hypothesis model for transmitter detection can be defined as follows:

$$x(t) = \begin{cases} n(t) & H_0 \\ hs(t) + n(t) & H_1 \end{cases}$$

where $x(t)$ is the signal received by the CR user, $s(t)$ is the transmitted signal of the primary user, $n(t)$ is a zero-mean additive white Gaussian noise (AWGN) and h is the amplitude gain of the channel. H_0 is a null hypothesis, which states that there is no licensed user signal in a certain spectrum band. On the other hand, H_1 is an alternative hypothesis, which indicates that there exists some primary user signal.

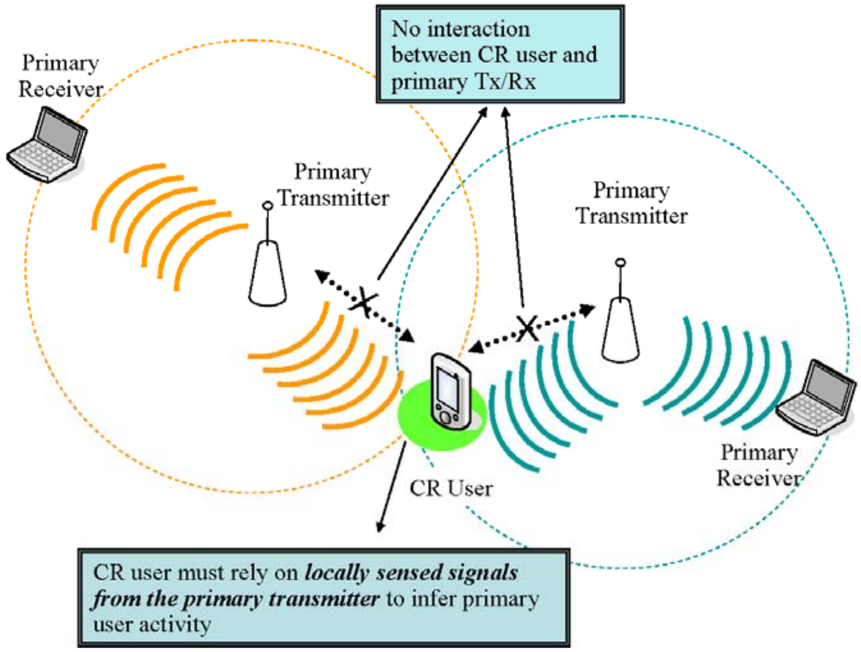


Figure 17: Primary transmitter detection (from [43]).

Three schemes are generally used for the transmitter detection: *matched filter detection*, *energy detection* and *feature detection* [44].

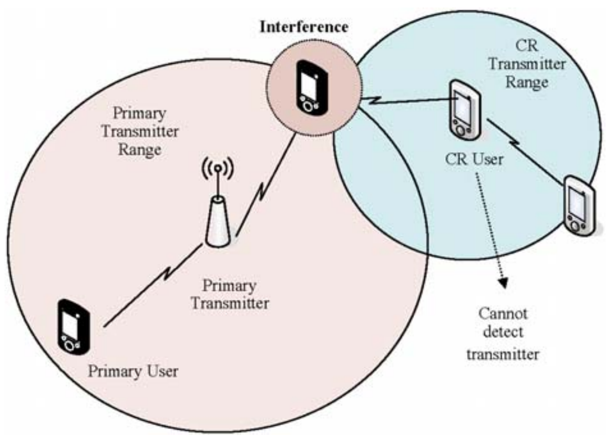
Matched Filter Detection When the information of the primary user signal is known to the CR user, the optimal detector in stationary Gaussian noise is the matched filter for maximizing the signal to noise ratio (SNR) in the presence of additive stochastic noise. This detection method requires only $O(1/SNR)$ samples to achieve a detection error probability constraint [44]. However, the matched filter requires not only a priori knowledge of the characteristics of the primary user signal but also the synchronization between the primary transmitter and the CR user. Hence, if this information is not accurate, then the matched filter performs poorly.

Energy Detection If the receiver cannot gather sufficient information about the primary user signal, for example, if the power of the random Gaussian noise is only known to the receiver, the optimal detector is an energy detector. In the energy detection, CR users sense the presence/absence of the primary users based on the energy of the received primary signal. In order to measure the energy of the received primary signal, the received signal is squared and integrated over the observation interval. Finally, the output of the integrator is compared with a threshold to decide if a primary user is present.

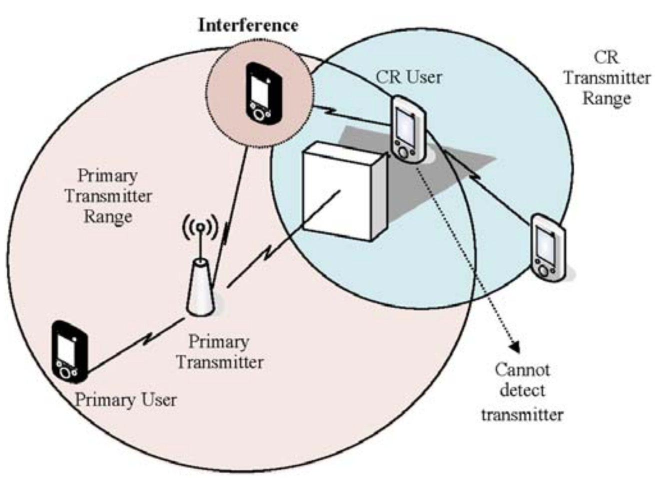
The energy detector requires $O(1/SNR^2)$ samples for a given detection error probability. Thus, if CR users need to detect weak signals (SNR: -10dB to -40 dB), the energy detection suffers from longer detection time compared to the matched filter detection [44].

While the energy detector is easy to be implemented, it can only determine the presence of the signal but cannot differentiate signal types. Thus, the energy detector often generates the false detection triggered by the unintended signals. Another shortcoming is that since the energy detection depends only on the SNR of the received signal, its performance is susceptible to uncertainty in noise power. If the noise power is uncertain and can take any value in the range of x dB, the energy detector will not be able to detect the signal reliably as the SNR is less than the threshold $10\log_{10}10^{x/10}-1$, called an SNR wall [88]. For a detailed analysis and discussion on the fundamental role of SNR walls in sensing, see the seminal papers of Tandra and Sahai [89], [90]. For further discussion on properties of energy detectors, see [91], [92].

Cyclostationary Feature Detection Modulated signals are, in general, coupled with sine wave carriers, pulse trains, repeating spreading, hopping sequences, or cyclic prefixes, which result in built-in periodicity. Thus, these modulated signals are characterized as *cyclostationarity* since their mean and autocorrelation exhibit periodicity. The feature detector exploits this inherent periodicity in the primary user's signal by analyzing a spectral correlation function [93]. The main advantage of the feature detection is its robustness to the uncertainty in noise power. The feature detector distinguishes between the noise energy and the modulated signal energy, which is the result of the fact that the noise is a wide-sense stationary signal with no correlation, while the modulated signals are cyclostationary with spectral correlation due to the built-in periodicity. Furthermore, since the feature detector is also capable of differentiating different types of signals, it can tolerate false alarms caused by the external signals, such as those from other CR users or interference. Therefore, a cyclostationary feature detector can perform better than the energy detector in differentiating different signal types. However, it is computationally complex and requires significantly long observation time.



(a) Receiver uncertainty.



(b) Shadowing uncertainty.

Figure 18: Transmitter detection problem (from [36]).

Wavelet Detection: Sensing wideband spectrum with multiple sub-bands can be viewed as an edge detection problem. In the wavelet detection technique, wideband spectrum is considered as the continuous sub-bands where the power spectral characteristics are smooth within bands but change abruptly on the border of bands. By employing a wavelet transform of the power spectral density (PSD) of the observed signal $y(t)$, the singularities of the PSD $S_y(f)$ can be located and thus the vacant frequency bands can be found. The wavelet detection approach is particularly useful when detecting non-contiguous bands in the wide spectrum. In [87] Tian and Giannakis proposed a wavelet approach to wideband spectrum sensing for cognitive radios. Their solution is based on the gradient wavelet modulus and multi-scale wavelet products. The local maxima of the wavelet modulus have sharp variation points, and this principle is exploited for spectrum sensing purposes.

5.2.2 Receiver Detection

Although cooperative detection reduces the probability of interference, the most efficient way to detect spectrum holes is to detect the primary users that are receiving data within the communication range of a CR user. As depicted in Figure 19, the primary receiver usually emits the local oscillator (LO) leakage power from its RF front-end when it receives the signals from the primary transmitter. In order to determine the spectrum availability, a primary receiver detection method exploits this local oscillator (LO) leakage power instead of the signal from the primary transmitter and detects the presence of the primary receiver directly [94]. Such an approach may be feasible for TV receivers only or need further hardware such as a supporting sensor network in the area with the primary receivers.

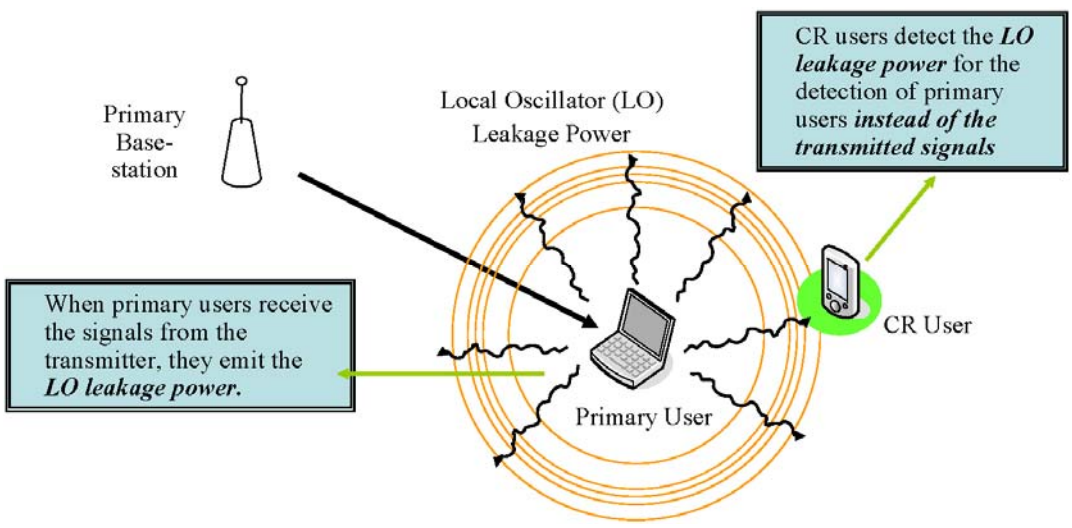


Figure 19: Primary receiver detection (from [43]).

5.3 *Cooperation*

Due to the lack of interactions between the primary users and the CR users, the transmitter detection techniques rely on the weak signals from only the primary transmitters. Hence, transmitter detection techniques alone cannot avoid the interference to primary receivers because of the lack of primary receiver's information as depicted in Figure 20. Moreover, transmitter detection models cannot prevent the hidden terminal problem. A CR user (transmitter) can have a good line-of-sight to a CR receiver, but may not be able to detect the primary transmitter due to shadowing as shown in Figure 20. Therefore, sensing information from other users is required for more accurate primary transmitter detection, which is referred to as *cooperative detection*. Cooperative detection is theoretically more accurate since the uncertainty in a single user's detection can be minimized through collaboration [95]-[97]. Moreover, the multi-path fading and shadowing effects can be mitigated so that the detection probability is improved in a heavily shadowed environment.

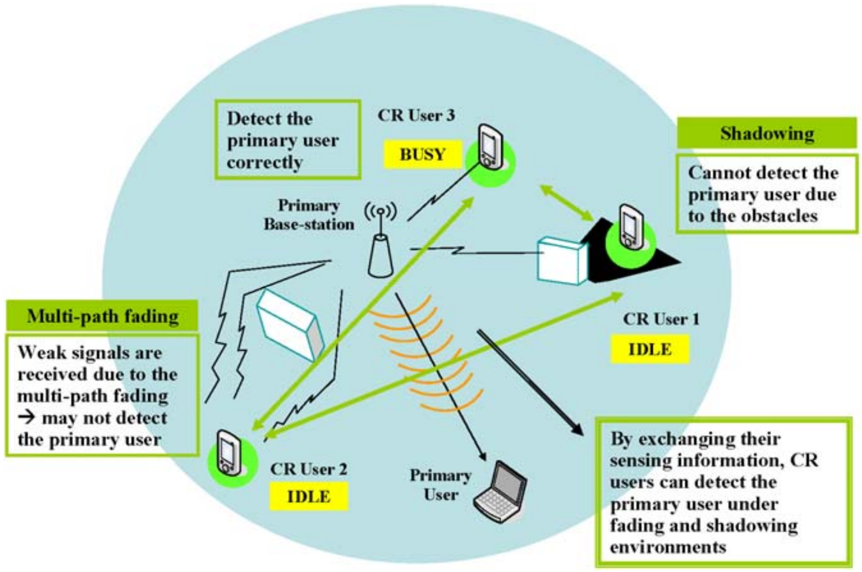


Figure 20: Cooperative transmitter detection under highly faded and shadowed environment.

Assume there are three CR users as illustrated in Figure 20. Since CR user 1 receives a weak signal (with a low SNR) due to the multi-path fading, it cannot detect the signal of the primary transmitter. CR user 2 is in the shadowing area so it cannot detect the primary user, either. Only CR user 3 detects the signal of the primary user correctly. In this case, CR users 1 and 2 will cause interference if they try to transmit based on their local observations. However, by exchanging sensing information with CR user 3, CR users 1 and 2 can detect the existence of the primary user even though they are under fading and shadowing environments.

As explained above, in traditional cooperative detection, the spectrum band is decided to be available only if no primary user activity is detected. Even if only one primary user activity is detected, CR users cannot use this spectrum band [95]. From this detection criterion, the cooperative detection probability $\overline{P}_d^c$ of N CR users is obtained by $\overline{P}_d^c = 1-(1-\overline{P}_d)^N$ where $\overline{P}_d$ is the detection probability of the individual CR user.

While this decision strategy surely increases the detection probability, it increases the cooperative false alarm probability, $\overline{P}_f^c = 1-(1-\overline{P}_f)^N$ where $\overline{P}_f$ is the false alarm probability of the individual CR user, which leads to lose more spectrum opportunities. Furthermore, cooperative approaches cause adverse effects on resource-constrained networks due to the overhead traffic

5.4 *Sensing Control*

The main objective of spectrum sensing is to find more spectrum access opportunities without interfering with primary networks. To this end, the sensing operations of CR users are controlled and coordinated by a sensing controller, which considers two main issues on: (1) how long and frequently CR users should sense the spectrum to achieve sufficient sensing accuracy in in-band sensing, and (2) how quickly CR user can find the available spectrum band in out-of-band sensing, which are summarized in Figure 21.

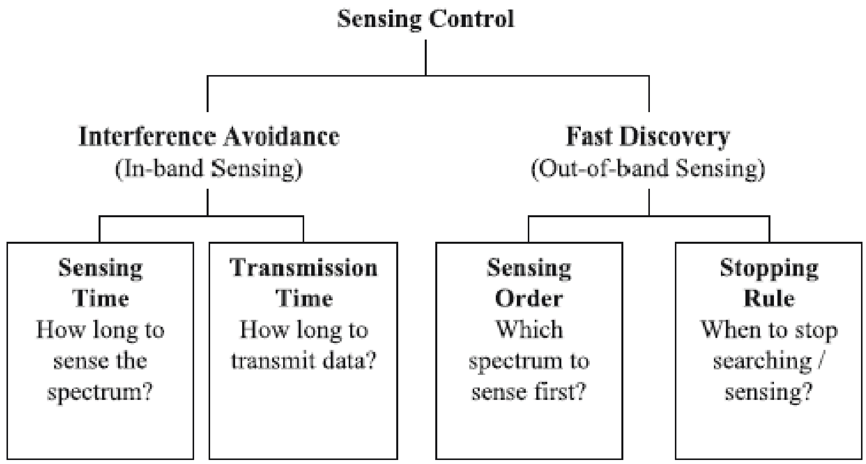


Figure 21: Configuration parameters coordinated by sensing control (from [43]).

5.4.1 In-band Sensing Control

The first issue is related to the maximum spectrum opportunity as well as interference avoidance. The in-band sensing generally adopts the periodic sensing structure where CR users are allowed to access the spectrum only during the transmission period followed by sensing (observation) period. In the periodic sensing, longer sensing time leads to higher sensing accuracy, and hence to less interference. But as the sensing time becomes longer, the transmission time of CR users will be decreased. Conversely, while longer transmission time increases the access opportunities, it causes higher interference due to the lack of sensing information. Thus, how to select the proper sensing and transmission times is an important issue in spectrum sensing.

Sensing time optimization is investigated in [98] and [99]. In [99], the sensing time is determined to maximize the channel efficiency while maintaining the required detection probability, which does not consider the influence of a false alarm probability. In [98], the sensing time is optimized for a multiple spectrum environment so as to maximize the throughput of CR users.

The focus in [100] and [101] is on determining optimal transmission time. In [101], for a given sensing time, the transmission time is determined to maximize the throughput of the CR network while the packet collision probability for the primary network is under a certain threshold. However, similar to [99], this method does not consider a false alarm probability for estimating collision probability and throughput. In [100], a maximum transmission time is determined to protect multiple heterogeneous PUs based on the perfect sensing where no detection error is considered. All efforts stated above, mainly focus on determining either optimal sensing time or optimal transmission time. On the other hand, in [79], a theoretical framework is developed to optimize both sensing and transmission times simultaneously in such a way as to maximize the transmission efficiency subject to interference avoidance constraints where both parameters are determined adaptively depending on the time-varying cooperative gain.

5.4.2 Out-of-Band Sensing Control

In the case of the cognitive radio ad hoc networks (CRAHNs) when a CR user needs to find new available spectrum band (out-of-band sensing), a spectrum discovery time is another crucial factor to determine the performance of the CR network. Thus, this spectrum sensing should have a coordination scheme not only to discover as many spectrum opportunities as possible but also to minimize the delay in finding them. This is also an important issue in spectrum mobility to reduce the switching time.

First, the proper selection of spectrum sensing order can help to reduce the spectrum discovery time in out-of-band sensing. In [102], an n-step serial search scheme is proposed mainly focusing on correlated occupancy channel models, where the spectrum availability of current spectrum is assumed to be dependent on that of its adjacent spectrum bands. In [77] and [78], both transmission time and spectrum searching sequence are optimized by minimizing searching delay as well as maximizing spectrum opportunities.

Moreover, if the CR user senses more spectrum bands, it is highly probable to detect a better spectrum band while resulting in longer spectrum searching time. To exploit this tradeoff efficiently, a well-defined stopping rule of spectrum searching is essential in out-of-band sensing. In [103], an optimal stopping time is determined to maximize the expected capacity of CR users subject to the maximum number of spectrum bands a CR user can use simultaneously.

5.5 *Spectrum sensing classification*

Generally, from the different point of view, spectrum sensing can be different classification. Therefore, spectrum sensing can be classified three categories: cooperation with/without CR user, interaction with/without PU and the detected object. It is as shown in Figure 22. In the following sections, we describe these spectrum sensing classification methods for CR networks and discuss the open research topics in this area.

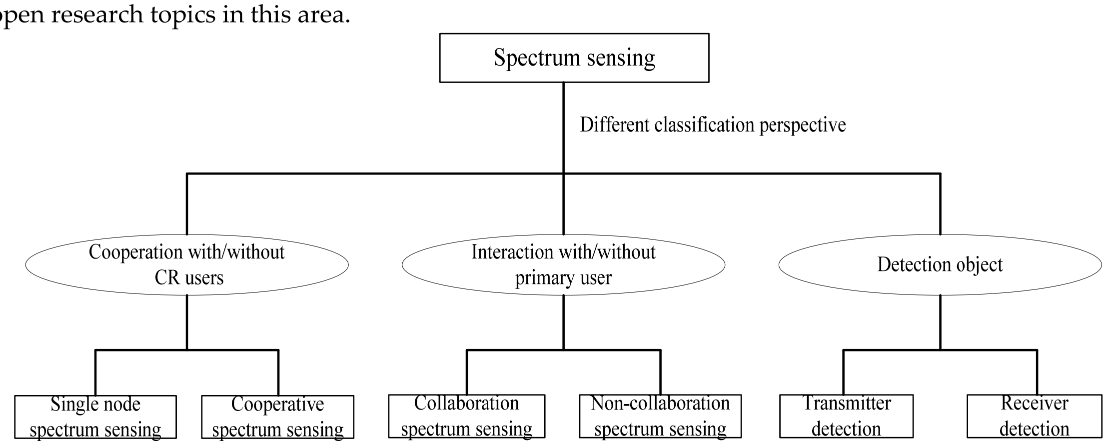


Figure 22: Classification of spectrum sensing.

5.5.1 **Cooperation with/without CR users**

From the point of view of cooperation with/without CR users, spectrum sensing can be classified into single node sensing and cooperative sensing.

5.5.1.1 Single node sensing

Single node sensing, which is also called as local sensing, means just one CR node determine if the primary user is present in a certain spectrum without cooperation between nodes. Therefore, single node sensing mainly focuses on some sensing algorithms including blind detection and feature detection.

5.5.1.2 Cooperative spectrum sensing

Due to the lack of interactions between the primary users and the CR users, spectrum sensing relies on the signals from only the primary users. When single node spectrum sensing, there is the hidden terminal problem, which happens when the cognitive user is shadowed or in deep fade. To address this issue, multiple cognitive users can be coordinated to perform spectrum sensing, which is referred to as *cooperative spectrum sensing*.

Cooperative spectrum sensing is theoretically more accurate since the uncertainty in a single user's detection can be minimized through collaboration. Moreover, the multi-path fading and shadowing effects can be mitigated so that the detection probability is improved in a heavily shadowed environment. In general, cooperative spectrum sensing is performed as follows:

Step 1: every cognitive user performs local spectrum measurements independently and makes a decision.

Step 2: all or partial of the cognitive users forward their decision to a fusion node which can be an AP in a wireless LAN or a BS in a cellular network.

Step 3: the fusion nodes combine those decisions and makes a final decision to infer the absence or presence of the PU in the observed frequency band.

5.5.2 Interaction with/without PU

From the point of view of interaction with/without PU, spectrum sensing can be classified into collaboration and non-collaboration spectrum sensing.

5.5.2.1 Collaboration spectrum sensing

When CR users have real-time interaction with the primary user, they can know the exact information on current spectrum band. Thus, CR users can reduce the sensing spectrum band number and sensing time, even not sensing.

5.5.2.2 Non-collaboration spectrum sensing

Since CR users are usually assumed not to have any real-time interaction with the primary users, they cannot know the exact information on current transmissions within the primary networks.

5.5.3 The detected object

From the point of view of the detected object, spectrum sensing can be classified into transmitter detection and receiver detection.

5.5.3.1 Transmitter detection

The more detailed description can be seen in Section 5.2.1.

5.5.3.2 Receiver detection

The more detailed description can be seen in Section 5.2.2.

5.6 *Radio-Source Localization*

A cognitive radio has the ability to capture or sense the information from its radio environment. If the gathered information is associated with the location of the radio-sources, we provide a more accurate view of the observed environment. For this purpose, ranging techniques are used for localization. These techniques provide local information in terms of distance or orientation related to the neighbours of a cognitive radio device. This local information can then be combined to provide location estimates.

Ranging techniques are based on message exchanges between CR users, corresponding signal strength, and timing measurements in the network. The received signal strength or the timing information can be converted into distance measurement. Similarly, the direction from which the signal has been received can be measured through sophisticated antenna configurations, and thus providing orientation information for the device with respect to its neighbours.

Local information from several neighbour CR users in terms of distance, orientation, or connectivity are usually combined to provide location estimates and minimize the erroneous information from a single measurement through multiple measurements. The individual measurements can be regarded as constraints for an optimization problem and the most likely location of the device can be estimated through maximum likelihood (ML) techniques.

While these techniques usually result in highly accurate location estimation, the processing required for optimization is significantly large. The formalization of the localization problems requires high processing power and memory. Consequently, most algorithms cannot be efficiently performed because of processing or memory constraints.

The computation constraints of the individual cognitive radio can be addressed through centralized solutions, where the constraints for a global optimization problem is determined by each CR user and sent to the CR base station. Then, the CR base station can solve this global problem and determine the locations of the nodes. While these centralized techniques are efficient in terms of processing, they incur high communication overhead and create single point of failure problems. Consequently, protocols with simple and distributed localization algorithms, which will not increase the processing or energy consumption of individual CR users, can be developed.

Next, we describe the ranging techniques in CR networks, namely: received signal strength, time of arrival, time difference arrival, and angle of arrival.

5.6.1 Ranging and Direction Detection Techniques

The ranging techniques are methods through which the distance or angle to a particular radio device can be found. The main ranging techniques are:

I. Received Signal Strength (RSS)

The most common ranging technique is based on received signal strength measurements. Since each CR user is able to report the received signal strength, this technique has minimal hardware requirements. The main idea is to estimate the distance of a transmitter device to a CR receiver using the following information:

- The power of the received signal,
- The knowledge of the transmitted power,
- The path loss model.

If the transmitted power is known by the receivers, the received signal strength can be used to estimate the distance with an error proportional to the uncertainty factor and the RSS measurement error. The accuracy of the RSS based ranging techniques is limited. First, the effects of shadowing and multipath may be severe and require multiple ranging measurements. Moreover, in cases where there is no line of sight between the transmitter and a CR receiver, the received signal strength measurements result in a significant error in distance measurements. If a CR user is not in the line of sight of the transmitter device because of an obstacle, it receives the transmitted signals through reflections from the environment. The signal received by the CR user traverses a longer path than the direct path and the reflected signal is attenuated more, which results in a longer distance measurement than the actual distance between the transmitter and the CR receiver. This type of error is more severe than multipath effects because multiple measurements cannot improve the distance estimate. Since each of the measurements is still based on reflected rays, the error in distance measurements cannot be corrected. Another major challenge with the RSS based distance measurements is the difficulty in estimating the parameters for the channel model.

II. Time of Arrival (ToA)

ToA techniques rely on accurate measurements of transmit and receive times of signals between two radios. These measurements are used to estimate the distance based on the propagation time and the speed of the signal. Since timing information is used for distance measurements, synchronization is essential for these techniques. ToA techniques require very accurate time measurement hardware to measure the actual received time of the signals. Any small error in time measurement can result in large distance estimate errors because of the high propagation speed of RF signals in air.

III. Time difference arrival (TDoA)

While actual propagation time measurements of a signal require sophisticated measurement hardware, the *difference* between the receive time of two separate signals can be used to estimate the distance between radio devices. Since less accurate measurements are tolerated, time difference of arrival (TDoA) techniques can be used for CR networks in practice.

IV. Angle of Arrival (AoA)

In addition to signal strength and time, the direction of the received signal can be very helpful for localization, assuming the Rx is endowed with the proper array of antennas, the right calibration, etc. Thus, all AOA techniques rely on directional antennas or special multiple antenna configurations to estimate the angle of arrival of the received signal. Such techniques can provide very high localization accuracy (much higher than the other techniques), depending on the AOA measurement accuracy. However, as mentioned, high-complexity antenna arrays are required for direction measurement, which increases the hardware and software cost (particularly if multiple RF chains are involved).

This spatial dimension embedded in the AOA dimension (in other words, multi-antenna reception) is a particularly potent mechanism for the REA mission and extensive literature exists on the subject in the past 30+ years. In fact, many such platforms exist and operate in the government space, particularly for airborne applications; the corresponding application of high-resolution direction-finding on the ground is more recent and less established as a proven-and-true technology due to the challenges of ground propagation. The classical array model in the standard literature assumes Line-of-Sight (LOS) environments with “clean” single-AOA paths. These techniques, however, typically cannot provide reliable AOA estimates in a multipath environment.

The traditional tools for AOA estimation (namely ESRPIT and MUSIC [104], [105]) have been based on forming the spatial correlation matrix and the performing eigen-value decomposition in order to arrive at signal and noise subspaces. In sum, if *L* statistically signals impinge on an *M*-element array, then the signal subspace is the one spanned by the eigenvectors corresponding to the *L* largest eigen-values, whereas the noise subspace is the one spanned by the eigenvectors corresponding to the *M-L* smallest eigen-values (also called “noise eigen-values”). Subspace-based algorithms use either one of these two subspaces to estimate the AOA’s, and their performance is limited by the accuracy of separating these two subspaces. A bound for AOA estimation (without channel multipath or delay spread) was derived in [106]. As mentioned above, however, these algorithms fail to provide reliable AOA estimates when they operate in a multipath environment. In order to modify the MUSIC-like processors in order to accommodate multiple paths (with a different AOA each) of the same signal source, a condition alternately called “fully-correlated signals” or “coherent multipath”, some special pre-processing (“spatial smoothing”) must take place [107]. Within this “classical” array-processing framework, only AOA estimation can be achieved and the maximum number of impinging signals that can be spatially separated is limited by the aforementioned bound. These limitations are due to the fact that (a) this model does not explicitly account for the inherent waveform structure of digital modulation formats and (b) the use of eigen-analysis limits the size of the search to the dimensions of the formed correlation matrix.

In contrast to the above philosophy, several studies ([108],[109]) have demonstrated that *likelihood-based* algorithms applied to the array-reception model provide performance superior to that of subspace-based algorithms. The former adopts a generic signal format (no special waveform details assumed) whereas the second models precisely the reception as a function of the digital modulation, the transmit- and receive-filters, the AOA *as well as* the TOA of the various arriving paths, etc. Likelihood-based algorithms are capable of operating in a variety of challenging propagation environments, including those with significant multipath. In particular, array modelling and processing procedure suitable for digital communication systems have been developed. This procedure in [108], termed JADE, utilizes training data sequences in order to estimate the overall channel which is then converted via traditional spatial-correlation-matrix formation and the use of subspace algorithms (e.g., MUSIC, ESPRIT) to AOA (and TOA) estimates. This procedure can be extended to operational environments where training data is not available (the so-called *blind* methods). Using innovative likelihood-based conversion algorithms, it has been demonstrated that reliable AOA estimation performance can be achieved using very small data records without the need for any training data. For cases where the difference of TOA's between paths is larger than 10% of the symbol duration, algorithms exist which estimate with accuracy the TOA's and AOA's of paths whose number may *exceed* the number of array elements. This approach is far more computationally efficient than other likelihood-based algorithms that have been suggested in the open literature. On the other hand, when the impinging propagation paths are even more closely packed in the time domain than the above-mentioned threshold of about 0.1T, it can be shown that the paths can be efficiently discerned only in the spatial (AOA) domain. Then, the number of physically distinguishable propagation paths is indeed upper-bounded by the number of array elements. For this case, an AOA-only conversion algorithm has also been developed which provides better performance than other classical AOA estimation algorithms. Algorithmic performance of any algorithm is always compared to the appropriately computed Cramer-Rao Lower Bound (CRLB).

After estimating position-related signal parameters, such as RSS, TOA, TDOA and AOA, as mentioned above, source position estimation is performed based on various techniques. An extended analysis of these techniques can be found in [110]. In particular, there exist two main categories of techniques:

• *Geometric* and *statistical techniques* estimate the location of the unknown device directly from the position related parameters estimated from the received signal by using geometric properties and statistical approaches respectively.

Geometric techniques are further divided into the following main classes:

- LATERATION. The lateration approach uses one of the following localization input parameters:
  TOA, TDOA and RSS. The position of the unknown terminal is estimated by measuring its distances from multiple known terminals and finding the intersection of circles or spheres.

- ANGULATION. Angulation is performed by exploiting the AOA measurements. The location of the unknown terminal is found by computing the intersection of the lines connecting the unknown and the known terminal. In order to improve accuracy multiple known terminals as well as highly directional antennas might be employed.

- HYBRID. The hybrid approach suggests the combination of two or more of the above mentioned types of position related parameters (such as TDOA/AOA, TOA/TDOA, TOA/AOA) in order to locate the unknown source. For example, using the hybrid TOA/AOA technique the object position can be estimated by using a single reference point.

The main disadvantage of geometric methods is that they fail to capture the effects of measurement errors. In order to combat this drawback of geometric techniques, statistical techniques suggest the adoption of a probabilistic model, namely a model which describes the observation space stochastically. In particular, in such a model the estimated position-related parameters are given by a sum of a deterministic term describing the unknown source location and an additive noise term describing measurement errors. The statistical characteristics of the additive noise term normally depend on the unknown source location. Statistical techniques are classified as *parametric* or *non-parametric* depending on whether a probabilistic description of the observation space is available or not, respectively.

PARAMETRIC. Parametric methods assume complete or partial knowledge of the probability density function (pdf) of the noise term in the estimated position-related parameters and view positioning as a detection/estimation problem. Therefore, Bayesian or maximum likelihood (ML) techniques can be employed depending on whether the *a priori* probability distribution of the unknown location is given or not. Parametric methods for positioning systems are proposed and analyzed in [111]-[119].

NON-PARAMETRIC. In cases where information about the pdf of the elements of the observation Space is unavailable non-parametric methods are applicable. The basic idea behind non-parametric techniques is to estimate a number of position-related parameters by introducing redundancy compared to estimation performed by a geometric location algorithm. This redundancy allows, through proper algorithms, to overcome the effects of measurement errors. In particular, one of the major issues in non-parametric estimation is the mitigation of NLOS effects. NLOS identification and mitigation methods are presented in [120], [121], [122].

• *Mapping (fingerprinting)* techniques exploit the information from a database [123] that consists of previously estimated position-related parameters corresponding to known locations. The database is usually obtained by a training (*offline*) phase before the positioning procedure starts.

Data storing and processing capabilities become certainly higher in the last years. Furthermore, network based geometrical techniques perform poorly in various urban and indoor environments. These observations have strengthened the importance of mapping techniques. Mapping techniques operate in two steps: they first collect features (fingerprints) of a scene and then estimate the location of an object by matching *online* measurements with the closest *a priori* location fingerprint. More precisely, in the first step (offline stage), which is based on a set of training data, the database of location fingerprints is built by performing a survey of the site where the system will be deployed. In the offline phase most of the proposed schemes use RSS measurements. However, in practice, the choice of fingerprints largely depends on available parameters and also on their impact on the performance of the localization algorithm. During the second step (online stage), the currently observed signal parameter and the previously collected information are combined in order to localize the unknown device.

5.7 *Examples of Sensing Techniques in Existing Applications*

In this subsection, we present examples of sensing techniques in existing applications: energy detection for wireless microphones, cyclostationary spectrum sensing for OFDM signals, and cyclostationary spectrum sensing for UMTS FDD signals [127].

5.7.1 Energy detection for wireless microphones

The wireless microphones, known as part 74 devices in the US, are unlicensed low power radio transmitting devices. Detection of part 74 devices is mandatory for IEEE802.22 systems. The emitting power is about 10mW. The one that operates on frequencies in the broadcast television bands uses Frequencies Modulation. The voice and music produces 20Hz-20kHz band, and when modulated the radio frequency band does not exceed 100kHz, depending on the deviation.

The algorithm detects short band signal (100kHz) within UHF channels (6 or 8 MHz) for any type of modulation. The process begins with a signal sampling at 8MHz. The samples are stored is a buffer and an N-points FFT algorithm is processed over the buffer. The tone spacing is B_c/N where B_c is the channel bandwidth, and has to be less than the signal bandwidth B_s. A sliding window, as large as the searched signal bandwidth, sweeps the spectrum, and the average power over this window is computed. If the signal occupies the channel, the window position contains the maximum power P_{max}. Thus, P_{max} is compared with a threshold value Th. The signal is detected if $P_{max} > Th$. If there is only noise, the threshold is always greater than P_{max}.

5.7.2 Cyclostationary spectrum sensing for OFDM signals

The cyclostationary detector applies to OFDM signals and particularly IEEE-802.11g compliant signals. The algorithm [128] jointly exploits the correlation induced by the cycle prefix and the fact that this correlation is time periodic, i.e. the fact that the OFDM signal is a cyclostationary signal. For each OFDM symbol, a part of its end is copied at its beginning, which is the so-called cyclic prefix. This induces a correlation between the OFDM signal and its time-shifted version.

The cyclostationary detector calculates the autocorrelation function $R_y(u,m)$ of the received OFDM signal $y(u)$. $R_y(u,m)$ is a periodic function of u with period $\alpha_0^{-1}=N+D$, where N is the number of OFDM carriers and D is the length of cyclic prefix. As this function depends on u in a periodic way, the signal $y(u)$ is not a stationary but a cyclostationary signal. Its autocorrelation function can be written as a Fourier series. The Fourier coefficient $R_y^{(k\alpha_0)}(N)$ is called the *cycle correlation coefficient* at *cyclic frequency* $k\alpha_0$ and at time lag N for nonzero integer k. Therefore, the distinct features of OFDM signals with different number of carriers, symbol periods, and cyclic prefix lengths can be detected and identified in the cyclic frequency domain.

5.7.3 Cyclostationary spectrum sensing for UMTS FDD signals

DS-CDMA signals can be detected exploiting the baseband cyclostationary properties come from the redundancy between frequency components separated by multiples of the symbol rate, i.e. the cyclic feature appears at $\alpha=1/(SF\cdot Tc)$, where SF is the spreading factor and Tc is the time chip duration. However, UMTS FDD standard employs, in addition to user specific spreading, so called scrambling sequences, in order to improve the correlation characteristics of the signals and provide base station identification [129]. Scrambling take place over multiple symbols, with period equal to 10 ms, removing the cyclostationarity with the symbol rate. Nevertheless in UMTS standard, user signals have always the same chip rate, even if the individual SF and symbol rates differ. Thus $\alpha_c = 1/Tc$ (3.84 Mchip/s) is a common cyclic frequency to all downlink signals and the most appropriate to detect the received signal. An analytical formulation of the cyclic autocorrelation function for a UMTS FDD signal at $\alpha_c = 1/Tc$ can be found in [130].

The cyclostationary feature detector exploits the cyclic frequency common to all downlink signals in a UMTS cellular scenario, which comes from the UMTS chip rate, assuming the CR user knows the UMTS carrier frequencies and bandwidths. For that, the proposed detector, using a periodogram approach, relies on second order statistics, based on spectrum cyclic density function. The output of the detector, after all signal processing, is a detection statistic, d, in dB, which represents the ratio between the power of the cyclostationary feature measured at cyclic frequency, α_c, and the estimated noise floor measured at α_n. Simulation results, considering an AWGN channel, show that for an SNR of -10 dB and an observation time of at least 30 ms it is possible to assure a 99.9% probability of detection while having a negligible probability of false alarm, which is also possible for 10 ms of observation time if the SNR is at least -5 dB. An extensive analysis of the sensitivity of the algorithm to realistic impairments (synchronization, frequency offset, multipath) is extensively discussed in [131].

5.8 *Spectrum Sensing Challenges*

Spectrum sensing constitutes one the most important components of the cognitive radio operation as highlighted in this chapter. The accuracy and the overhead of the spectrum sensing are two main issues in this area. The solutions discussed so far in this chapter provide valuable insight to the challenges and potential solutions in spectrum sensing. Nevertheless, there still exist several open research challenges that need to be investigated for the development of accurate and efficient the spectrum sensing solutions. We discuss these challenges in detail in this section.

5.8.1 Multi-user CR Networks

CR networks usually reside in a multi-user environment, which consists of multiple CR users and primary users. Furthermore, CR networks can also be co-located with other CR networks competing for the same spectrum band. However, current interference models [132] do not consider the effect of multiple CR users. Multi-user environment makes it more difficult to sense the primary users and to estimate the actual interference. First, the effects of the transmission of other CR users are unknown to a specific CR user. Consequently, it is hard to estimate the total interference that would be caused at a primary receiver. Second, the transmissions of other CR users may prevent a specific CR user from detecting the activity of a primary transmitter and regard the primary user transmission as noise. This leads to degradation in sensing accuracy. Spectrum sensing functions should be developed considering the possibility of multi-user/network environment. In order to solve the multi-user problem, the cooperative detection schemes can be considered, which exploit the spatial diversity inherent in a multi-user network.

5.8.2 Physical Layer Constraints

Spectrum sensing techniques require efficient physical layer capabilities in terms of wideband sensing and rapid spectrum switching. However, the constraints of the physical layer need to be known to design practical sensing algorithms. The fact that the cognitive radio cannot sense and transmit simultaneously is one of the factors in the design of spectrum sensing algorithms. This fact has been considered in [79] to optimally schedule the transmission and sensing without degrading the sensing accuracy. As an alternative, the effect of using multiple radios has been investigated in [133], where a two transceiver operation is considered such that a transceiver always listens to the control channel for sensing. This operation improves the system performance; however, the complexity and device costs are high.

Another constraint is the limited spectrum sensing capabilities of cognitive radios. In other words, scanning the whole spectrum takes time. Since sensing consumes energy this process has to be carefully scheduled. One of the main requirements of CR networks is the detection of the primary users in a very short time [88], [134]. Since sensing time is important, OFDM-based CR networks are known to be excellent fit for the physical architecture of CR networks [38], [135], [136] . Since multi-carrier sensing can be exploited in OFDM-based CR networks, the overall sensing time can be reduced. Once a primary user is detected in a single carrier, sensing in other carriers is not necessary. In [135], a power-based sensing algorithm in OFDM networks is proposed for detecting the presence of a primary user. It is shown that the overall detection time is reduced by collecting information from each carrier. However, this necessitates the use of a large number of carriers, which increases the design complexity. Hence, novel spectrum sensing algorithms need to be developed such that the number of samples needed to detect the primary user is minimized within a given detection error probability. In this sense, cooperative spectrum sensing mechanisms can be exploited to overcome the constraint of each cognitive radio. The superiority of cooperative techniques in terms of system performance has already been demonstrated in many studies [79],[141], [142], [144]. On the other hand, such collaboration increases the communication overhead and may lead to overall system performance degradation when channel capacity or energy consumption is considered. Consequently, effective spectrum sharing techniques that enable efficient collaboration between different CR nodes in terms of spectrum sensing information sharing are required.

5.8.3 Cooperative Sensing

Cooperative sensing constitutes one of the potential solutions for spectrum sensing in CR networks. Spectrum sensing accuracy for a single user increases with the sensing time. Considering the sensing capabilities of CR radios, however, an acceptable accuracy may be reached only after very long sensing times. The uncertainty in noise, however, prevents even infinite sensing times from being accurate in some cases. This theoretical finding motivates cooperative sensing schemes.

Cooperative sensing, although more efficient, creates additional challenges for accurate spectrum sensing in CR networks. The communication requirement of the cooperating nodes necessitates cross-layer techniques that support joint design of spectrum sensing with spectrum sharing. Efficient communication and sharing techniques are necessary to alleviate the effects of communication overhead in cooperative sensing techniques. To this end, dynamic common control channel techniques, which provide a common control channel for the CR users to exchange spectrum sensing information, may be required [144]. Moreover, efficient and distributed coordination solutions that partition the spectrum sensing tasks to various co-located CR users are required.

5.8.4 Compressed Sensing

There are important technical challenges in wideband spectrum sensing, including both hardware and algorithmic problems. One way to perform wideband spectrum sensing is to employ a bank of tunable narrowband bandpass filters at the radio front-end to sense one narrow frequency band at a time. Simple algorithms such as energy or feature detection allow the detection of active users in one narrowband. As wireless communication systems of today operate on portions of spectrum having a lot of narrow frequency bands, this solution requires an excessively large number of radiofrequency components. As a complementary solution, software defined radio has raised lot of interest because of its wideband processing ability enabling to search multiple narrowbands simultaneously. Despite the small number of RF components required, processing wideband signals requires high speed DSP and a very high sampling rate that equals at least the Nyquist rate. Considering the limited time and processing capacity of mobile cognitive devices, neither of these two solutions seems to be feasible in terms of data storage, processing power and implementation complexity.

The theory of compressed (or compressive) sensing, a novel sensing/sampling paradigm, proposes a feasible solution by rendering signal recovery possible from samples obtained at sub-Nyquist rates. Compressed sensing emerged recently in the literature [137], [138], and has been applied successfully for signal reconstruction from incomplete frequency information. The compressed sensing paradigm aims at reconstructing a sparse signal represented in some basis, from few random measurements. For example, one may reconstruct a signal spectrum, which is sparse, from few randomly located time samples.

In the context of cognitive radio, assuming a sparse spectrum, i.e. a spectrum with lot of unused narrowbands, recent studies on compressed sensing [139], [140] have demonstrated that a random sub-Nyquist sampling enables an exact recovery of the spectrum. The advantage is two-fold. First, it enables to reduce the number of samples to be stored and processed. Secondly, the reconstruction property holds for any random sampling pattern. The random sampling pattern can model multiple unsynchronised sensing devices sampling the radio signal. Then, these devices can share their computational capabilities to reconstruct the spectrum and to detect vacant bands. Unlike collaborative detection, this method does not require synchronization between collaborative sensors.

5.8.5 Mobility

Spectrum sensing techniques aim to provide a map of the spectrum in a CR user's vicinity. Consequently, efficient spectrum decision techniques can be used. However, if a CR user moves, the spectrum allocation map may change rapidly. Therefore, the spectrum allocation map constructed by the sensing algorithm may become obsolete with high mobility. Therefore, the CR user may need to perform spectrum sensing as the user changes location. This necessitates an adaptive spectrum sensing technology that is responsive to the mobility of the CR user.

5.8.6 Adaptive Spectrum Sensing

The requirements of spectrum sensing solutions may depend on the network architecture. While centralized solutions focus on efficient information collection from multiple sensing devices and optimally allocating spectrum for users, distributed architectures lead to frequent information exchange between each CR user. Consequently, the nature of the spectrum sensing solution may differ depending on the architecture. However, considering that CR user devices will need to adapt to any network setting, whether being centralized or distributed, adaptive spectrum sensing solutions are crucial for rapid proliferation of the CR technology. As a result, a single CR device can be used in different network settings with a single, adaptive spectrum sensing solution.

Adaptive techniques are also necessary for different underlying physical layer functionalities. As explained above, physical layer constraints significantly affect the performance of spectrum sensing solutions. Moreover, it is clear that the realization of cognitive radio networks will lead to the implementation of different CR devices by different companies similar to the current case with WLANs. To provide a seamless spectrum sensing for higher networking layers, spectrum sensing solutions need to be adaptive to the physical layer capabilities.

5.8.7 Security

From the primary user point of view, CR users can be regarded as *malicious* devices that *eavesdrop* on the channel that the primary user is transmitting. In a sense, spectrum sensing techniques resemble eavesdropping attacks. In order to preserve the privacy of the users, spectrum sensing techniques need to be carefully designed. This is particularly important considering the economics that lie behind the primary networks. Since each primary user owns the particular spectrum, the traffic flowing through this spectrum needs to be protected. Spectrum sensing techniques, however, necessitate the knowledge of the existence of primary users for efficient operation. Consequently, spectrum sensing techniques should be designed in a way that they are aware of the *existence* of the ongoing traffic but cannot determine the *content* of the traffic. Moreover, these techniques need to be implemented so that any CR user that performs spectrum sensing will not be regarded as malicious by the already existing security protocols in primary networks.

6 Spectrum Sharing[1]

Cognitive Radio (CR) users can adaptively change their transmission parameters according to the changes in the radio environment. Moreover, a CR node should be able to detect an unused spectrum, select the best available channel for transmission, vacate the channel when licensed users are detected and coordinate access to this channel with other users. The shared nature of the wireless channel and multiple transmission attempts of the CR users are the main reasons for the existing challenges that spectrum sharing poses. Spectrum sharing provides fair spectrum scheduling, by coordination as well as adaptive allocation of communication resources among users. The two key functionalities of spectrum sharing are *resource allocation* and *spectrum access*. CR users select the proper channels (channel allocation) and adjust their transmission power (power control) in order to achieve the user requirements as well as resource fairness. Spectrum access enables multiple CR users to share the spectrum resource by determining who and when will access the channel. Different requirements are set for different approaches as shown on Figure 23.

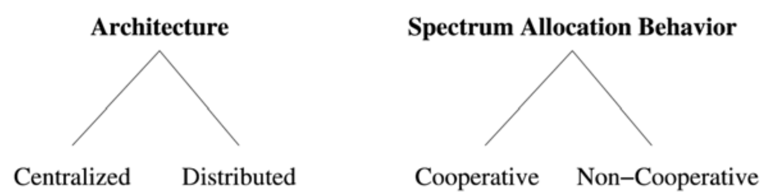


Figure 23: Classification of spectrum sharing based on architecture, and spectrum allocation behaviour (adapted from [36]).

6.1 *Overview of Spectrum Sharing Techniques*

The existing solutions for spectrum sharing in CR networks can be mainly classified in three aspects: i.e., according to their *architecture assumption*, *spectrum allocation behaviour*, and *spectrum access technique*.

The first classification for spectrum sharing techniques in CR networks is based on the architecture as follows:

- *Centralized Spectrum Sharing:* In these solutions, a centralized entity controls the spectrum allocation and access procedures [51], [145], [146].

- *Distributed Spectrum Sharing:* Distributed solutions are mainly proposed for cases where the construction of an infrastructure is not preferable [133], [141]-[144], [147]-[149]. Accordingly, each node is responsible for the spectrum allocation and access is based on local (or possibly global) policies.

The second classification for spectrum sharing techniques in CR networks is based on the access behaviour. More specifically, the spectrum access can be *cooperative* or *non-cooperative* as follows:

- *Cooperative Spectrum Sharing:* Cooperative (or collaborative) solutions consider the effect of the node's communication on other nodes [141]-[145], [147]. In other words, the interference measurements of each node are shared among other nodes. Furthermore, the spectrum allocation algorithms also consider this information. While all the centralized solutions can be

[1] Even though in Section 3.4 spectrum sharing was defined as sharing between CR users, in this section we extend the concept to incorporate sharing between CR users and PU.

regarded as cooperative, there also exist distributed cooperative solutions.

- *Non-cooperative Spectrum Sharing:* Contrary to the cooperative solutions, non-cooperative (or non-collaborative, *selfish*) solutions consider only the node at hand [133], [148], [149]. While non-cooperative solutions may result in reduced spectrum utilization, the minimal communication requirements among other nodes introduce a tradeoff for practical solutions.

Finally, the third classification for spectrum sharing in CR networks is based on the access technology as was already discussed above, and further explained below in Section 6.8.3:

- *Overlay Spectrum Sharing:* Overlay spectrum sharing refers to the spectrum access technique used. More specifically, a node accesses the network using a portion of the spectrum that has not been used by licensed users [133], [141], [144], [145], [147]- [149]. As a result, interference to the primary system is minimized. As also mentioned above, some authors call this "Interweave Spectrum Sharing".

- *Underlay Spectrum Sharing:* Underlay spectrum sharing exploits the spread spectrum techniques developed for cellular networks [142], [143]. Once a spectrum allocation map has been acquired, a CR node begins transmission such that its transmit power at a certain portion of the spectrum is regarded as noise by the licensed users. This technique requires sophisticated spread spectrum techniques and can utilize increased bandwidth compared to overlay techniques.

- *Cooperative Spectrum Sharing*: In this sharing model the secondary network is aware of the signal characteristics of the primary network which are exploited to achieve an enhanced performance for the secondary network by minimizing the interference resulted from the primary transmissions. This is also called "Overlay Spectrum Sharing" by some authors.

In the following sections, we explain the existing spectrum sharing techniques that are combinations of all these three classifications.

6.2 *Intra-Network Spectrum Sharing*

6.2.1 Overview

When secondary users try to access available spectrum holes, without causing interference in the same network, an intra network spectrum sharing technique is needed. There are many different proposed solutions in this area in terms of the classification showed on Figure 23.

6.2.2 Cooperative Intra-Network Spectrum Sharing

A significant amount of work on spectrum sharing focuses on intra-network spectrum sharing, where the users of a CR network try to access the available spectrum without causing interference to the primary users. Cooperative networks can be further divided into *centralized* and *distributed* cooperative networks.

In [49] the Dynamic Intelligent Management of Spectrum for Ubiquitous Mobile-access Network (DIMSUMNet) architecture is introduced. DIMSUMNet is a spectrum leasing scheme which temporarily leases the free channels from a wide range of primary user spectrum bands called the coordination access bands (CAB). The CAB may include idle channels from different primary user systems like cellular communication, PCS or TV spectrum. This protocol constructs a geographical map of the spectrum allocation termed as spectrum allocation map (SAM) which is used for the channel (CAB) allocation.

In [145], the dynamic spectrum access protocol (DSAP), which is a centralized solution for spectrum sharing in CR networks, is presented. DSAP is a centralized spectrum allocation scheme which is similar to the DIMSUMNet in terms of the architecture and operation. However, the DSAP allocates spectrum from the unlicensed spectrum (e.g. ISM band) instead of the licensed spectrum. Hence it can be viewed as a scheme with which the unlicensed users belonging to different wireless technologies can co-exist.

The DSAP proposed in this work enables a central entity to lease spectrum to users in a limited geographical region. DSAP consists of clients, DSAP server, and relays that relay information between server and clients that are not in the direct range of the server. Moreover, clients inform the server their channel conditions so that a global view of the network can be constructed at the server. By exploiting cooperative and distributed sensing, DSAP servers construct a *RadioMap*. This map is used for channel assignments which are leased to clients for a limited amount of time.

For distributed CR networks, a cooperative local bargaining (LB) scheme is proposed in [141] to provide both spectrum utilization and fairness. The local bargaining framework is formulated based on the framework in [150], [151]. Local bargaining is performed by constructing local groups according to a poverty line that ensures a minimum spectrum allocation to each user and hence focuses on fairness of users. The evaluations reveal that local bargaining can closely approximate centralized graph colouring approach at a reduced complexity. Moreover, localized operation via grouping provides an efficient operation between a fully distributed and a centralized scheme

Another approach is represented by Heterogeneous Distributed MAC (HD-MAC) protocol [144], in which local groups for spectrum sharing are provided (similarly to the previous protocol), but without the existence of a global control channel. Instead, a control channel is defined for every specific cluster on which nodes will exchange information. Moreover, if this channel is occupied, users are reorganized to use another available channel in the local cluster. The performance evaluations have shown that distributed clustering of nodes outperforms the case when a single control channel exists in a network, especially when traffic load is high.

The Dynamic Open Spectrum Sharing MAC (DOSS-MAC) protocol incorporates busy tones [147]. The main idea is to send a busy tone signal through the associated busy tone channel when when the transmitter and the receiver are communicating. FFT-based radio and non-coherent modulation/demodulation are proposed in order to further eliminate control channel communication. SC/MC-ADP protocol is also proposed for cooperative inter network spectrum sharing [142]. Each node announces its price to other nodes. Having this information, the node can first allocate a channel. In case if another node exists in that channel, it will determine the transmit power in order to eliminate the interference. In this way multiple users can use the same channel by adjusting their transmit power. This protocol can be classified as hybrid protocol of overlay and underlay techniques. The SC-ADP algorithm provides higher rates to users compared with selfish algorithms, where users select the best channel without any knowledge about the neighbours' interference.

6.2.3 **Non-Cooperative Intra-Network Spectrum Sharing**

In a non-cooperative scheme, users allocate channels based on their observations and interference patterns. For instance, the Device Centric Spectrum Management scheme (DCSM) [152] performs channel allocation in respect to 5 different rules. Users allocate channels according to these rules, based on their own observations, not collaborating with other users. Random access techniques are used to resolve contention in case more than one node chooses the same channel. Compared to cooperative schemes, these rule based algorithms show slightly worse performances. However, the communication overhead is reduced significantly.

Another approach, tailored for ad-hoc networks exploiting the access procedures used in IEEE 802.11 standards (like RTS/CTS and NAV), is proposed in [133]. Moreover, a common control channel is used such that transmitter receiver handshake is initiated through this channel.

In [153] a random access protocol, based on *spectrum etiquettes* principle presented in [154], is proposed in order to achieve weighted airtime fairness. A distributed version of it, in which only local information is exploited by users to take decisions, is proposed as well. In particular, in this distributed approach, users follow a *homo egualis society* model in which each user tries to reduce the inequalities with respect to the rest of the users in terms of averaged cumulative time spent using the spectrum. Even if this approach does not guarantee the theoretically optimal performance (in terms of airtime fairness), the simulations performed show results close to it.

Figure 24 shows a simple architecture in case of cooperative and non-cooperative distributed intra network spectrum sharing. It clearly shows the difference between these two approaches. In the non-cooperative case, users sense the spectrum and make channel allocations individually without mutual interactions. In the cooperative case, users make decisions on the basis of the information received from their neighbours.

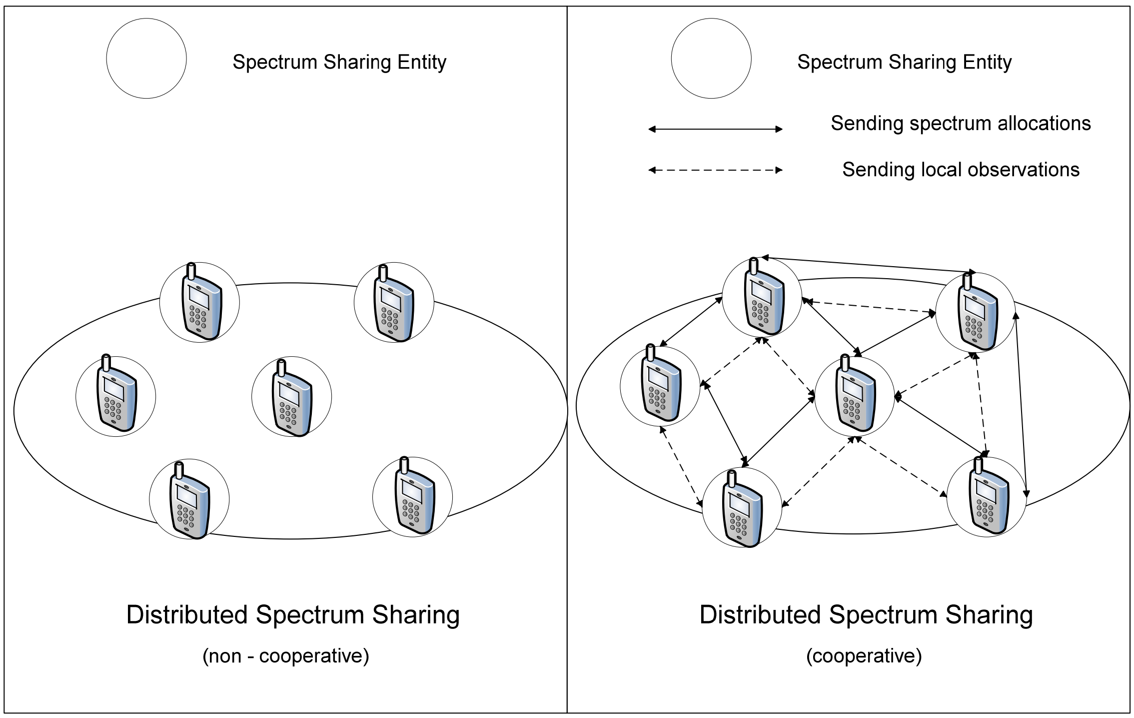


Figure 24: Intra network spectrum sharing for cooperative and non-cooperative distributed network (adapted from [155]).

Figure 25 shows an architecture for a centralized network where spectrum sharing algorithms are designed in a way that distributed users communicate with a central server that has the knowledge of the spectrum map in the area.

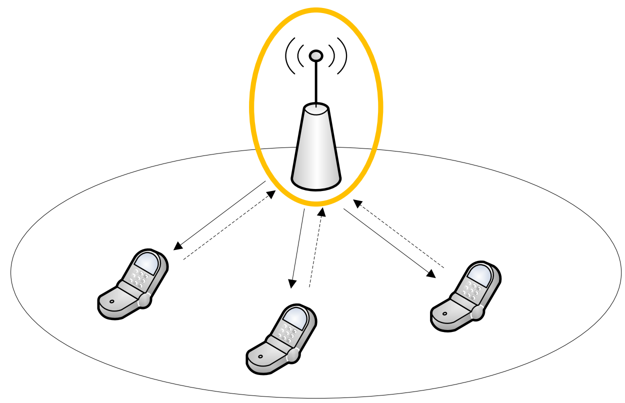


Figure 25: Spectrum sharing for centralized network (adapted from [155]).

6.3 *Inter-Network Spectrum Sharing*

Spectrum sharing among different systems or centralized allocations between different access points of a system is regulated via static frequency assignment. However, cognitive networks pose new and different challenges to inter network spectrum sharing. Figure 26 depicts the difference between inter and intra network sharing.

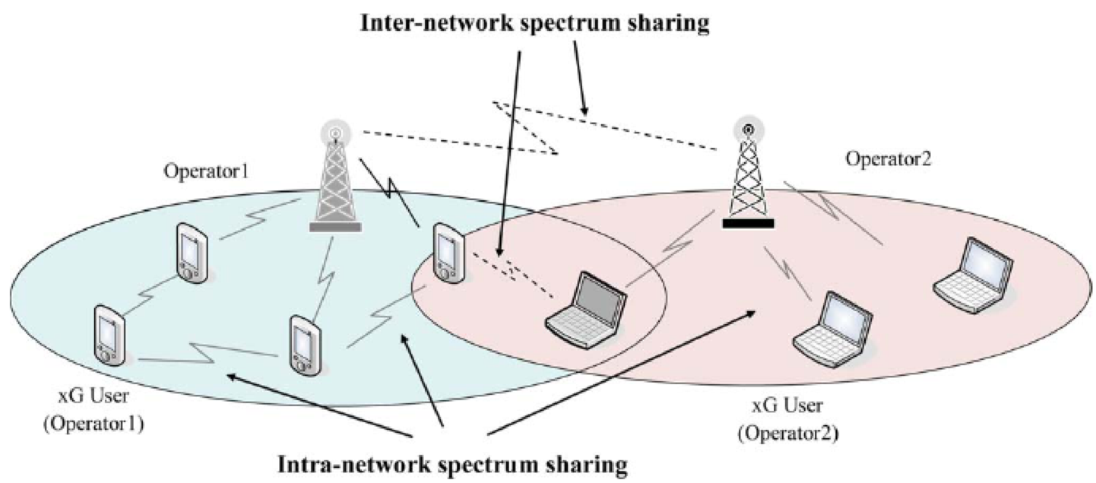


Figure 26: Intra and inter network sharing (from [36]).

Up to date, inter-network spectrum sharing has been regulated via static frequency assignment among different systems or centralized allocations between different access points of a system in cellular networks. In ad-hoc networks, only the interference issues in the ISM band has been investigated focusing mostly on the coexistence of WLAN and Bluetooth networks.

6.3.1 Spectrum Broker-Based Method

A distributed spectrum sharing scheme for wireless Internet service providers (WISPs) that share the same spectrum is proposed in [156], where a distributed QoS based dynamic channel reservation (D-QDCR) scheme is used. The basic concept behind D-QDCR is that a base station (BSs) of a WISP competes with its interferer BSs according to the QoS requirements of its users to allocate a portion of the spectrum. The basic unit for channel allocation in D-QDCR is called Q-frames. When a BS allocates a Q-frame, it uses the control and data channels allocated to it for coordination and data communication between the users. The competition between BSs is performed according to the priority of each BS depending on a BS's data volume and QoS requirement. Moreover, various competition policies are proposed based on the type of traffic a user demands. Although thorough evaluations are not provided in [156], the D-QDCR scheme serves an important contribution for inter-network spectrum sharing.

A major problem for the existing solutions in the cognitive network architecture is the requirement for a common control channel.

6.3.2 Etiquette Protocol

The etiquette protocol is proposed for coexistence of different networks [157]. It is assumed that every node is equipped with a cognitive radio and low-bit rate narrow-band control radio. The coordination is established between nodes by broadcasting CSCC messages [157]. Users periodically broadcast spectrum usage information (including user ID such as IEEE MAC address, frequency band used and transmit power as well as optional parameters such as technology type, service type, multi-hop forwarding capabilities if any, user priority, etc.). Each user adapts its transmission parameters based on the spectrum sensing. The CSCC protocol improves throughput by 35-160% in both frequency and power allocation.

In [50], a central spectrum policy server (Broker)- SPS is proposed to coordinate spectrum demands of multiple CR operators. In this scheme, each operator bids for the spectrum indicating the cost it will pay for the duration of the usage. The SPS then allocates the spectrum by maximizing its profit from these bids. The operators also determine an offer for the users and users select which operator to use for a given type of traffic. When compared to a case where each operator is assigned an equal share of the spectrum, the operator bidding scheme achieves higher throughput leading to higher revenue for the SPS, as well as a lower price for the users according to their requirements. This work opens a new perspective by incorporating competition for users as well as the spectrum in CR networks

The concept of centralized and distributed network architecture and inter network spectrum sharing approach is shown in Figure 27.

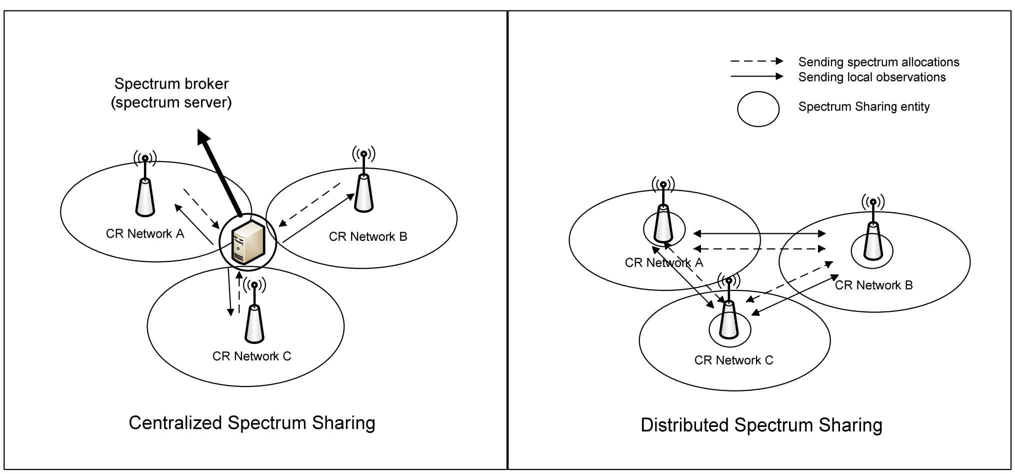


Figure 27: Inter network spectrum sharing (adapted from [155]).

6.4 *Game Theory for Spectrum Sharing*

Every CR node has the interest to use the spectrum as much as possible. However CR users have competing interest to maximize their own share of the spectrum resources. The activity of a one CR node can jeopardize the activity of another CR node. Therefore, CR users need to make intelligent decisions on spectrum usage and communication parameters based on the sensed spectrum dynamics and other users' decisions.

Game theory is a mathematical tool that analyzes the strategic interactions among multiple decision makers. Three major components in the game theory models are: the set of players, the strategies/action space of each player and the utility/payoff function, which measures the outcome of the game for each player. In cognitive radio networks, the competition and cooperation among the CR users can be well modelled as a spectrum sharing game. Specifically, in horizontal spectrum sharing, the players are all secondary users that compete for unlicensed spectrum. In licensed (vertical) spectrum sharing, where primary users lease their unused bands to secondary users, the players include both the primary and secondary users. The strategy for each player may vary according to the specific spectrum sharing scenario. For instance, the strategy of secondary users in open spectrum sharing may include the transmission parameters they want to adopt, such as the transmission power, access rate, time duration, etc. On the other hand, in licensed spectrum sharing, their strategy may include e.g. which licensed bands they want to use and how much they would pay for leasing those licensed bands. From the primary users' perspective, this also means to which secondary users they would lease each of their unused band and how much they will charge for each band. The utility functions for different users are accordingly defined to characterize various performance criteria. In unlicensed (horizontal) spectrum sharing, the utility function for the secondary users is often defined as a non-decreasing function of the Quality of Service (QoS) they receive by utilizing the unlicensed band. In licensed spectrum trading, the utility function for the users often represents the monetary gains (e.g. revenue minus cost) by leasing the licensed bands. In a non-cooperative spectrum sharing game with selfish network users, each user only aims to maximize its own utility by choosing an optimal strategy. The outcome of the non-cooperative game is often measured by the Nash Equilibrium (NE). The NE is defined as the set of strategies for all the users such that no user can improve its utility by unilaterally deviating from the equilibrium strategy given that the other users adopt the equilibrium strategies. The NE indicates that no individual user would have the incentive to choose a different strategy [158].

As one of major theoretical analysis approaches to spectrum sharing, game theory has been exploited for performance evaluation of CR spectrum access schemes. Especially, the comparison between cooperative and non-cooperative approaches has been presented in [159] through game theoretical analysis. In [159], game theory is exploited to analyze the behaviour of the cognitive radio for distributed adaptive channel allocation. It is assumed that users deploy CDMA and determine the operating channel and the coding rate by keeping transmission power constant. It is shown that the cooperative case can be modelled as an exact potential game, which converges to a pure strategy Nash equilibrium solution. However, this framework has been shown not to be applicable for non-cooperative spectrum sharing and a learning algorithm has been proposed. The evaluations reveal that Nash equilibrium point for cooperative users is reached quickly and results in a certain degree of fairness as well as improved throughput. On the other hand, the learning algorithm for non-cooperative users converges to a mixed strategy allocation. Moreover, the fairness is degraded when non-cooperative approach is used. While this approach results in slightly worse performance, the information exchange required by selfish users is significantly low.

Depending on the relationship between the components of a game, game theoretical approaches can exploit diverse game models. Among them, the following game models are mainly considered for spectrum sharing:

Normal (or strategic) form game: This is a simple and basic model in game theory. In this model, all players make their decisions simultaneously and this process occurs only once for each player. Furthermore, they are assumed to be aware of not only their own utility functions but also the utility functions for all the other players in the game.

Repeated game: This model is defined as a sequence of stages, where each stage is a normal form game. Based on the past actions, current observations, and future expectations, players determine their actions at each stage. The actions of each player are assumed to be synchronized. In this model, the action strategies can be updated in each stage adapting to the actions and outcomes observed previously. Based on the outcome of each stage of the game, the players can incorporate punishment and reward strategies, which are well suited for wireless networks. If a player deviates from the previously negotiated strategy, the other players choose their actions so as to reduce the outcome of the offending player.

Asynchronous myopic repeated game: A myopic repeated game is a repeated game where the strategy update of a player is based on only its observation of the game at the most recent stage. Since players in a myopic repeated game are not able to consider future outcomes in determining the current actions, they employ simpler myopic strategies, instead of complex multi-stage strategies used in general repeated games. Here, all decisions at each stage are made simultaneously, similar to the classical repeated games. However, the myopic repeated games model may not be feasible for distributed wireless networks, such as CR ad hoc networks (CRAHNs). This is because CRAHNs may require random or asynchronous decisions due to the absence of a central network entity. In this case, an asynchronous myopic repeated game provides a better model for spectrum sharing, in which decisions do not have to be made synchronously. In this model, the actions of each player adapt to the most recent state of networks under a variety of different decision timings.

Mixed (or probabilistic) strategy game: Some of normal form games may not have a steady-state solution, called Nash equilibrium where no selfish CR user has incentive to unilaterally change its action. To overcome this limitation, game theoretic approaches introduce a mixed strategy game, where players employ their strategies based on the probabilities of each action. This approach achieves the Nash equilibrium even though it does not exist in pure strategies. Although the game theoretic approaches can achieve the Nash equilibrium, they cannot guarantee the Pareto optimum, leading to lower network capacity.

6.5 *Cooperative Relays for Spectrum Sharing*

In order to improve the spectrum utilization, cooperative relays have been recently introduced to spectrum sharing in CR networks [160], where a relay node with rich available spectrum bands acts as a bridge for communication between a source and a destination nodes. Figure 28 shows a typical cooperative relay system for cooperative spectrum sharing, where CR users co-exist with multiple PUs, PUs 1, 2, 3, and 4, and their corresponding licensed spectrum bands, CHs 1, 2, 3, and 4, respectively. Without loss of generality, we consider a three-terminal CR relays system, which consists of source, relay, and destination. As shown in the Figure 28, those available spectrum bands can support dual-hop transmission (CHs 1 and 2), relay transmission (CH 3), and direct transmission (CH 4). Therefore, spectrum heterogeneity observed at source, relay, and destination nodes brings new challenges to cooperative relays.

In [161], relays have been used for balancing traffic request and spectrum resource. In [162], the idea of using unused bands via relay nodes has been proposed to increase spectrum utilization. In [163], the method of using common bands via relay nodes to enhance the *signal-to-noise ratio* has been studied. However, existing works with a single relay consider separate end-to-end transmissions between the relay node and other nodes. In other words, how to perform cooperative relays with all available spectrum bands at these three terminals has not been addressed. Thus, the overall end-to-end performance can be further improved by advanced cooperative relay design.

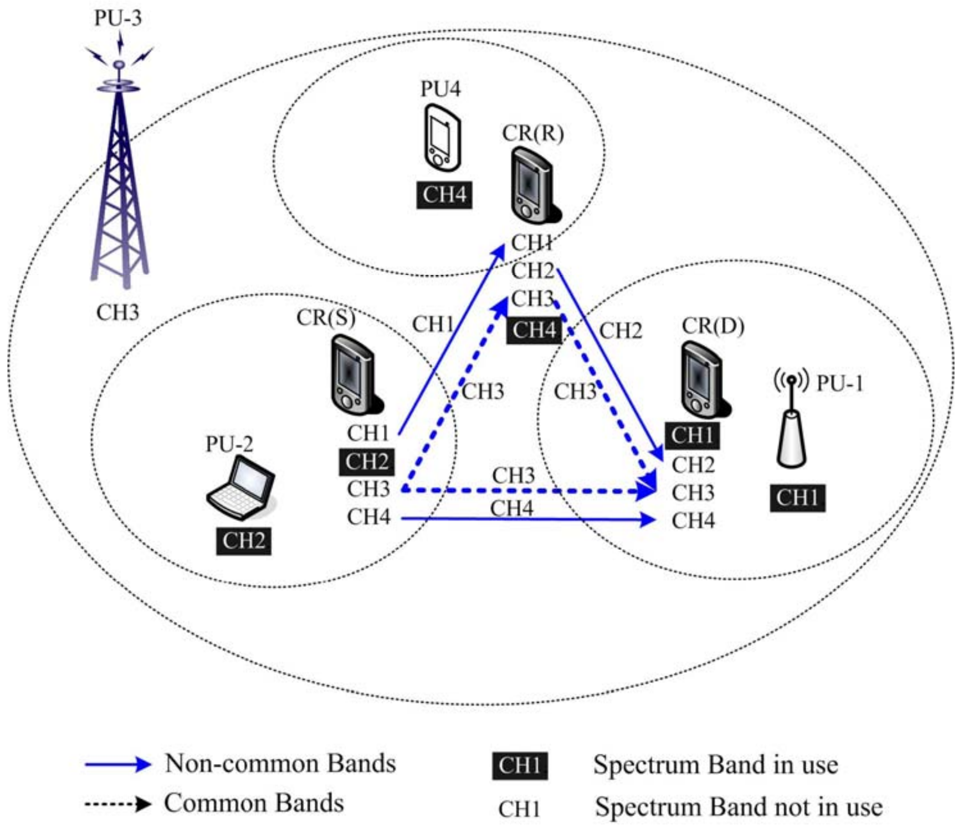


Figure 28: Cooperative Relays.

6.6 *Hierarchical spectrum sharing*

In the hierarchical spectrum sharing (HSS) paradigm [164], unlicensed users may be allowed to opportunistically access the temporarily unused licensed band of a primary system, as long as they do not generate harmful interference to primary users. However, opportunistic use of the spectrum must consider spectrum heterogeneity, which refers to the situation where the available spectrum of one CR user is unavailable to another. Spectrum heterogeneity results from primary users' mobility and traffic variation, interference constraints and rewards on each spectrum band. In order to exploit such spectrum heterogeneity, the hierarchical spectrum sharing network (HSSN), which available spectrum is classified into two categories, is proposed. In HSSN, each type of available spectrum is used for its specific scenarios.

The goal of the HSSN is to extend available spectrum and obtain a better spectral utilization in CR networks. Its design handles two important characteristics of such networks: variations in spectrum availability and interference constraints. Variations in spectrum availability imply that the available spectrum for one CR user may be unavailable to another, which is related to the locations of CR users. The interference constraints are mainly how to avoid interference to primary users and decide whether CR users are allowed to use certain spectrum bands given a certain power constraint.

In the HSSN, available spectrum bands detected by CR users are classified into two categories according to their interference levels, and then different spectrum bands are used for different scenarios. A HSSN can be deployed in a mixed manner, both as an infrastructure network and as an ad hoc network, as shown in Figure 29.

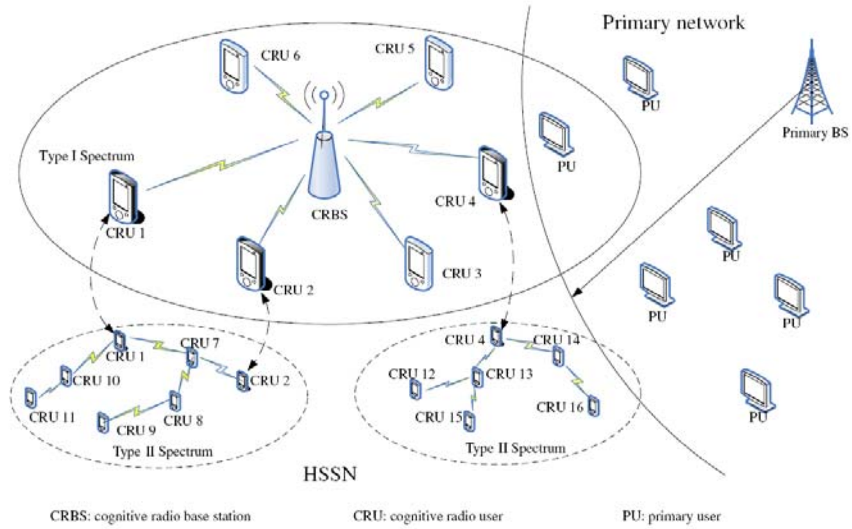


Figure 29: The HSSN architecture (from [164]).

There are two communication modes in the HSSN: point to multi-point mode and ad hoc mode. Cognitive radio user (CRU) can either communicate with each other in a single-hop or a multi-hop manner, or access the cognitive radio base station (CRBS) directly. Different communication modes adopt different available spectrum bands. Available spectrum bands in this network are classified into two categories: Type I and Type II. Type I is with high power sharing and used for direct communication between CRUs and CRBS while Type II is with low power sharing and used for direct communication among CRUs. In other words, different types of available spectrum can be used in different scenarios in the HSSN.

6.7 *Spectrum Sharing Challenges*

Past few years have witnessed extensive research done in the field of cognitive networks and spectrum sharing techniques. Even though great progress is achieved, there are still many open research issues for realization of efficient and seamless open spectrum operation. The following text considers some of the open research challenges.

6.7.1 **Dynamic Radio Range**

The radio range changes constantly with the operating frequency due to attenuation variation. In many cases of analyzed algorithms, a fixed radio range is assumed. In cognitive networks, user decisions depend upon neighbour measurements interference profile of the spectrum. The interference profile for a node changes as neighbours change their transmission frequency. Due to this property, the choice of a control channel needs to be carefully decided. It would be much more efficient to select control channels in the lower frequencies of the spectrum where the transmission range will be higher and to select data channels in the higher frequencies of the spectrum where a localized operation can be utilized with minimized interference. Operation frequency aware spectrum sharing techniques can be an interesting challenge due to the direct interdependency between interference and radio range [36].

6.7.2 **Spectrum Unit**

Almost all spectrum sharing techniques discussed in the previous sections consider a channel as the basic spectrum unit for operation. The term channel has not yet been precisely determined.

Different algorithms and methods have been proposed to select the suitable channel for efficient operation in cognitive networks.

It is clear that the definition of a channel as a spectrum unit for spectrum sharing is crucial in further developing algorithms. Furthermore, the existence of primary users and the heterogeneity of the networks that are available introduce additional challenges to the choice of a spectrum unit/channel. The necessity of a spectrum space for a spectrum unit is also advocated. The possible dimensions of the spectrum space are classified as power, frequency, time, space, and signal. Although not orthogonal, these dimensions can be used to distinguish signals. A three dimensional space model for modelling network resources has been proposed. A Virtual Cube concept has been proposed based on the three dimensions. The Virtual Cube concept defines a unit structure based on the resource allocation techniques used in the existing networks [36]. The three dimensional resource-space with time, rate, and power/code dimensions cube is shown on Figure 30.

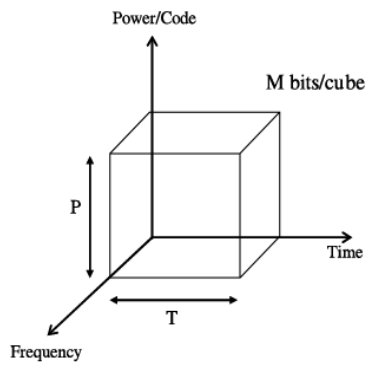


Figure 30: Virtual cube model (from [36]).

The time dimension models the time required to transfer information. The rate dimension models the data rate of the network. Thus, the capacity of different networks with the same connection durations but different data rates is captured in the rate dimension. In the case of CDMA networks, the bandwidth increase due to the multi-code transmissions is also captured in this dimension. The power/code dimension models the energy consumed for transmitting information through the network. Different networks MAC procedures vary in terms of the power consumption by the wireless nodes. Hence, a third dimension represented as the power levels for transmission is required, because of different modulation schemes, error coding and channel coding techniques that different users use.

Using this spectrum unit, heterogeneous access types in existing networks as well as cognitive network spectrum can be modelled. Determining a common spectrum unit is crucial for efficient utilization of the wireless spectrum and seamless operability with existing primary networks.

Although there already exists a vast amount of research in spectrum sharing, there are still many open research issues for the realization of efficient and seamless open spectrum operation. In the following, we detail the challenges for spectrum sharing in CR networks along with some possible solutions.

6.7.3 Distributed Power Allocation

The CR user in CRAHNs determines the transmission power in a distributed manner without support of the central entity, which may cause interference due to the limitation of sensing area even if it does not detect any transmission in its observation range. Thus, spectrum sharing necessitates sophisticated power control methods for adapting to the time-varying radio environment so as to maximize capacity with the protection of the transmissions of PUs.

6.7.4 Topology Discovery

The use of non-uniform channels by different CR users makes topology discovery difficult. For example, two CR users A and B experience different PU activity in their respective coverage areas (channels 1 and 2 available for CR A and channel 3 for CR B) and thus may only be allowed to transmit on mutually exclusive channels. The allowed channels for CR A (1,2) being different from those used by CR B (3) makes it difficult to send out periodic beacons informing the nodes within transmission range of their own ID and other location coordinates needed for networking.

6.7.5 Spectrum Access and Coordination

In classical ad hoc networks, the request to send (RTS) and clear to send (CTS) mechanism is used to signal control of the channel and reduce simultaneous transmissions to an extent. In CR networks, however, the available spectrum is dynamic and users may switch the channel after a given communicating pair of nodes have exchanged the channel access signal. Thus, a fresh set of RTS-CTS exchange may need to be undertaken in the new channel to enforce a silence zone among the neighbouring CR users in the new spectrum. Moreover, the CR users monitoring the earlier channel are oblivious to the spectrum change on the link. They continue to maintain their timers and wait for the duration needed to complete the entire data transfer before initiating their own transmission. This leads to inefficient spectrum use, and new coordination mechanisms among the CR users is necessary whenever the spectrum access conditions change.

6.7.6 Reactivity to topology modifications

In mobile networks the topology changes quite often, leading to frequent variations of interference profile. In this situation one of the critical points is the fastness of the system to react when the current spectrum sharing configuration does not fulfil anymore the user requirements. The risk is that, if the system needs long time to compute a new spectrum sharing configuration, the solution found could be not suitable anymore looking at the fact that topology could be varied with respect to the one that started the recalculation process. Hence, a technique that leads to a sub-optimal solution in a short amount of time could be preferred, in this context, to another one that requires a longer amount of time, but that finds the optimal solution.

More generally a special attention should be put in balancing, according to the scenario, convergence fastness and distance from the optimum.

6.8 *Resource Allocation and Spectrum Access*

Based on the observation on the determined spectrum band, the base stations in centralized CR networks or CR users in CRAHNs need to determine their communication resources intelligently. In the following subsections, we explain two main issues in resource allocation: channel allocation and power allocation.

6.8.1 Channel Allocation

The classical channel allocation problem has been widely studied in both dynamic and static contexts, and many of those results are relevant to CR networks as well [165]. Accordingly, we shall specifically focus in the following on the schemes that have been proposed for channel allocation in the CR context. If a CR user uses a frequency division multiple access where a single spectrum consists of multiple channels or orthogonal frequency division multiplexing (OFDM), it needs to determine channels or sub-carriers so as to satisfy their QoS requirements. For channel allocation, a graph colouring based collaborative spectrum allocation scheme is proposed in [150], where a topology-optimized allocation algorithm is used for the fixed topology. In mobile networks, however, the network topology changes due to the node mobility. Using this global optimization approach, the network needs to completely recompute spectrum assignments for all users after each change, resulting in high computational and communication overhead. Furthermore it may require a central network entity to control channel allocation.

For the resource-constrained networks such as sensor and ad hoc networks, a rule-based device centric spectrum management is proposed in [166]. In this method, instead of collaborating with other users, CR users access the spectrum independently according to both local observation and predetermined rules, leading to minimizing the communication overhead.

Distributed spectrum allocation via local bargaining is proposed in [167], where spectrum negotiation is made in small self-organized groups. Users affected by the mobility event self-organize into bargaining groups and adapt their spectrum assignment to approximate a new optimal assignment. Two types of bargaining algorithms are considered, i.e. one-to-one bargaining, where 3 nodes in total are enough to complete the bargaining or one-buyer-multi-seller bargaining, where all neighbouring nodes need to participate in the bargaining. The goal is to achieve fairness among users. Results have shown that the proposed bargaining approach performs similarly as the topology-optimized approach but with much less complexity. It is proposed that in a real system nodes can be selfish so that a pricing based bargaining or a rule based bargaining would be more practical.

Another approach is elaborated in [168]. The scheme is called Strongly Dominant Strategy Equilibrium (SDSE) and is used for non-cooperative networks. It incorporates a payment formula. The players (CR nodes) can pay or receive credit (spectrum allocation) from the system administrator (central server). In this manner, a global optimality effective system is achieved.

In [169] a distributed framework is proposed to allocate channels to users when they want to communicate in order to satisfy their data-rate requests and power constraints. After an analysis of the available channels and the potential data-rate achievable on each of them according to power constraints, each user that needs to communicate sorts the found channels based on the potential channel gain of each of them. Then it proceeds to select channels until it reaches the required data rate. After that each user keeps adapting the selected channels in order to take into account the choices of other users. Different additional rules are also proposed to advantage active users or, alternatively, new users that want to start a communication.

Although dynamic channel allocation has been considered quite deeply for deciding which white space opportunity to migrate, there has been much less work in the area of channel allocation or race condition between secondary users. Especially if the secondaries lack fast signaling channel to coordinate channel allocations to problem become more difficult load balancing problem. There has been recent interest to solve these sorts of problems by several groups, and e.g. the use of classical balls and bins algorithm has been proposed as a possible approach to solve this secondary problem [170], [171].

6.8.2 Power Allocation

In the power allocation, the CR user needs to adjust its transmission power by considering co-channel (or inter-user) interference. In addition, power allocation should be based on the PU activities in its transmission not to violate the interference constraints. Cooperation among neighbours helps to enhance the performance of spectrum sharing, especially in power allocation which should be aware of the PU activities in the transmission range.

In [172], spectrum sharing for unlicensed band is proposed based on the one-shot normal form game and repeated game. Furthermore, it is shown that orthogonal power allocation, i.e., assigning the channel to only one transmission to avoid co-channel interference with other neighbours, is optimal for maximizing the entire network capacity.

A different approach is proposed in [173], where both a Single Channel and Multi Channel Asynchronous Distributed Pricing (SC/MC-ADP) schemes are proposed. Every CR node announces its interference measurements (price) to others. Multiple users can coexist in one channel adjusting their transmitting power. The CR node first chooses a channel for transmitting. In case other users are already using that channel, the node would have to determine its transmission power in order to eliminate the co-existence interference. This method achieves higher performance compared to selfish algorithms, where users select the best channel without any knowledge for the transmission parameters of the neighbouring nodes. It is also shown that in a dense network with heavy interference, the SC-ADP algorithm can also perform better than the iterative water-filling algorithm where each user transmits over multiple channels but the users do not exchange any information. The efficiency loss of SC-ADP can be improved by using a large number of channels (MC-ADP), but diminishes as the number of channels decreases. Although this method assumes a static network with stationary channel gains, the SC-ADP algorithm can be applied to a dynamic spectrum sharing scenario, provided that the exchange of prices occurs on a slower time scale than the variations in interference. While this method considers the channel and power allocation at the same time, it does not address the heterogeneous spectrum availability over time and space which is a unique characteristic in CR ad hoc networks.

As described in [164], available spectrum bands are classified into two types to support both centralized and distributed communications simultaneously. A stable and efficient power allocation scheme is required to full make use of the potential of HSSN. In [174], a hybrid power allocation scheme in the HSSN is proposed. The proposed scheme is composed of three parts: a centralized power allocation scheme, a distributed power allocation scheme, and a coordination policy to coordinate these two types of power allocation schemes when both of them are exploited in the same channels. The centralized power allocation, which is performed when cognitive radio users (CRUs) are exploiting Type I spectrum bands, designs a two-step fair allocation scheme. In its first step, resources, such as channels and powers, are allocated by cognitive radio base station (CRBS) based on fairness and QoS requirements to obtain the maximum available resources of CRUs. In the second step, to get the final resource and reduce algorithm complexity, the allocation task is accomplished by each CRU simultaneously. The distributed power allocation, which is conducted within a cluster when CRUs are exploiting Type II spectrum bands, designs utility based power allocation algorithm combined with admission control. This utility function is formulated to reflect the needs of PUs and CRUs. Further, a coordination policy to combine centralized power allocation scheme with distributed power allocation scheme is also proposed when they are exploited in the same channels.

6.8.3 **Spectrum Access**

The inefficient spectrum use can be improved through opportunistic access to licensed bands without interfering with the existing users. In a cognitive network, multiple CR users are trying to access the spectrum simultaneously. Therefore, this access should be coordinated in order to prevent collisions in overlapping portions of the spectrum. Recall that based on the access technology, spectrum sharing techniques can be divided as *overlay* and *underlay* techniques [36]. Open access to most of the spectrum, even spectrum licensed for a dedicated technology, is only permitted by radio regulation authorities. Overlay spectrum sharing approach is when node accesses the network using a portion of the spectrum that has not been used by the primary users. As a result the interference is minimized. Overlay sharing requires new protocols and algorithms for spectrum sharing in order to nodes transmissions fit into the identified spectrum usage patterns, Figure 31. An underlay approach exploits the spectrum sharing techniques. The node transmits over a certain portion of the spectrum, regarded as noise by the licensed users. This technique requires sophisticated spread spectrum techniques, compared to overlay techniques, such as UltraWideBand (UWB). UWB is a transmission technique using pulses with very short time duration across a very large frequency band [174]. UWB transmissions are a part of the lower background noise from the perspective of other communication systems. Figure 31 shows how the multicarrier wideband system can change transmission powers, subcarrier spaces and subcarrier bandwidth to optimize spectrum usage.

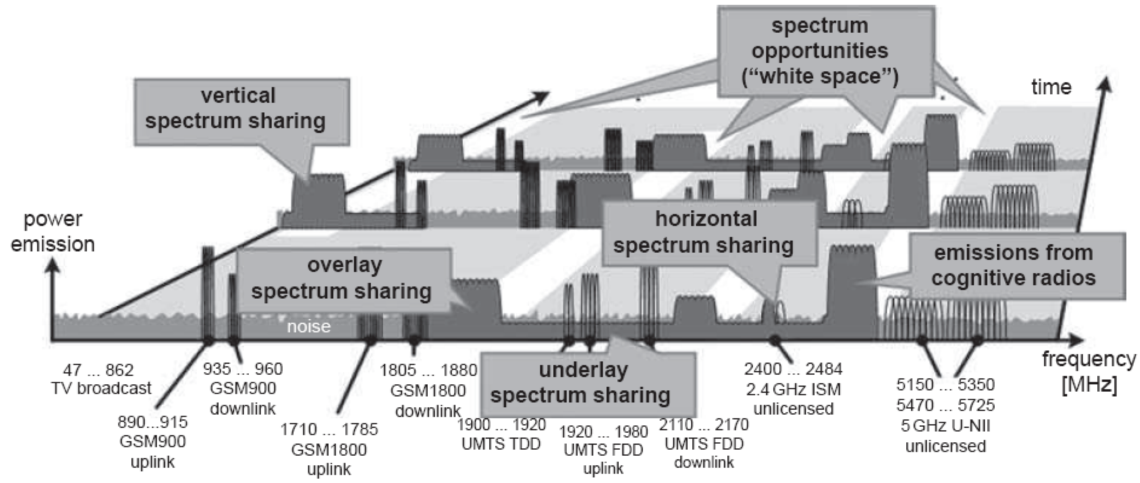


Figure 31: Opportunistic (secondary) spectrum usage with underlay spectrum sharing (low power) and overlay spectrum sharing (higher power, where spectrum opportunities, i.e. white space exist) (from [175]).

Overlay approach becomes more efficient than underlay when interference among users is high [36]. Comparisons of the overlay and the underlay approach can be made against the outage probability of the primary system. Usually, the overlay scheme outperforms the underlay scheme in terms of outage probability. Overlay approach results in poor performance when an inefficient spectrum sensing exists in the system.

Another approach is to use hybrid spectrum sharing techniques. In this approach, the node spreads its transmission over the entire spectrum and nulls or notch frequencies where a primary user is transmitting. Furthermore, when interference avoidance is incorporated, the underlay approach guarantees smaller outage probability than pure interference avoidance. Additional improvement of the hybrid approach is that a higher number of secondary users can be accommodated [36].

Theoretical analyses have also shown that cooperative settings result in higher fairness and spectrum utilization than non-cooperative. The trade-off exists between the higher performance achieved with cooperativeness and network overhead due to frequent information exchange in such networks. Also, considering the tradeoff between system complexity and performance, hybrid techniques may be considered as the most appropriate in some implementations.

CRs will have to share spectrum either with unlicensed wireless systems or with licensed wireless systems that are typically designed for exclusive use of the licensed spectrum, Figure 32. The sharing of licensed spectrum with primary wireless systems is referred to as *vertical spectrum sharing*. The sharing of unlicensed spectrum, i.e. sharing between users with similar regulatory priority, can be referred as *horizontal spectrum sharing*. Horizontal spectrum sharing also means sharing the same spectrum by dissimilar CR nodes (operated for example by different or even competing network operators), that are not designed to communicate to each other. Licensed and unlicensed spectrum bands are shown on Figure 32.

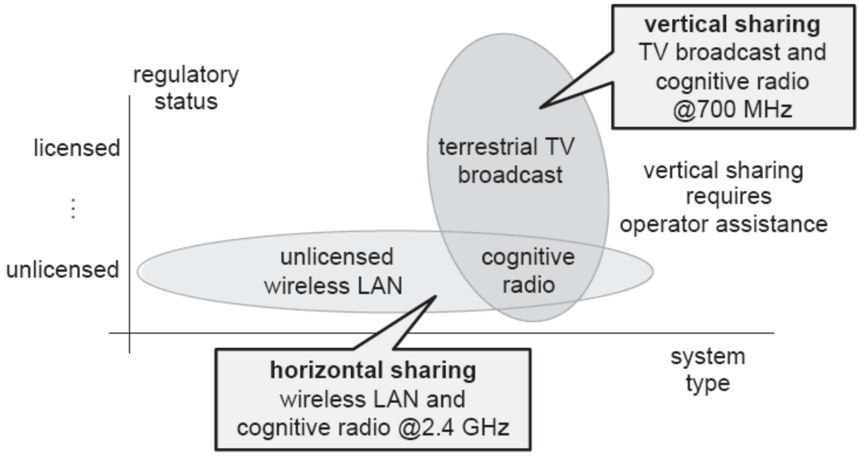


Figure 32: Vertical and horizontal spectrum sharing (from [174]).

CR nodes are able to operate without harmful interference in sporadically used licensed spectrum while requiring no modifications in the primary wireless network. Different, sophisticated access protocols are used in order to avoid collisions of CR nodes and greedy behaviour, when they access the licensed spectrum. In vertical sharing, operators can assist CR nodes to identify the unused spectrum holes in order to protect their transmissions. This can be referred as "operator assistance" [175]. In horizontal sharing, the CR nodes autonomously identify opportunities and coordinate their usage with other CR nodes. To avoid chaotic and unpredictable greedy spectrum usage, advanced approaches such as spectrum etiquette are helpful.

7 Resource Management and MAC Protocols

In addition to the techniques discussed in Section 6, spectrum sharing includes resource allocation and spectrum access. While resource allocation consists of power allocation and channel allocation, the spectrum access is governed by the CR MAC protocols in CR networks. In this section, we focus on the resource allocation and spectrum access via CR MAC protocols.

7.1 *Resource Management*

The Cognitive Radio Resource Management (CRRM) is the heart of the cognitive radio concept. The CRRM performs all aspects of the cognition cycle, thus resulting in "smarter" and more efficient resource utilization within a heterogeneous wireless network. A simplified block diagram architecture that can be used as a basis for CRRM implementation is depicted in
Figure 33.

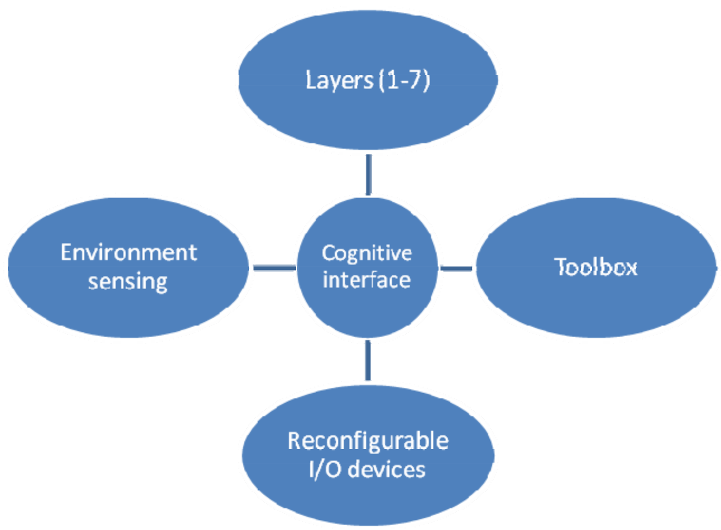


Figure 33: Simplified block diagram architecture for CRRM.

The CRRM is comprised of 4 key features [176], i.e. optimization, cross-layering, learning and reasoning. All of these features can be mapped in the cognition cycle. Optimization and reasoning are representations for the "decide" idiom, learning is located at the "learn" part and the cross-layering approach is general for all states of the cognition cycle.

7.1.1 **Optimization**

Resource management is an optimized solution for allocating network resources in order to increase the network performance. The optimization can be generally focused on optimizing either a single objective or a set of objectives. However, the nature of the wireless communications almost exclusively requires the multi – objective optimization. The optimization point of view to the cognitive radio paradigm is on how to formulate cognitive radio networking problems as optimization problems from the perspective of resource allocation. Multi - objective optimization can be executed following either the decision making theory concept or the game theory concept. The decision making theory attempts to reach an optimal solution through classical mathematical rationalization, whereas the game theory views the optimization problem as a game and tries to find the optimal way to "play" the game.

The decision making approach is based on formulating an objective function (i.e. the goal of the optimization), as well as on setting equality and inequality constraints that the optimal solution must not cross [177]. Three groups of solutions arise for this type of optimization approach, i.e. closed form solution, integer/combinatorial programming and mathematical programming.

The closed form solution [177] is the general decision making optimization understanding, where an optimization goal is reached by using approximations and solving Lagrangian equations in closed form.

The integer/combinatorial programming [177] encompass the optimization problems that involve parameters with integer values or parameters that are of combinatorial nature. These are multi - objective problems that can be solved only as a search for the optimal answer through the entire set of possible answers. The goal of the integer/combinatorial programming is shortening the search to a smaller subset of possibilities. The possible solutions for the integer/combinatorial optimization include relaxation and decomposition, enumeration, cutting planes and solutions to the knapsack problem [177].

Most of the real world optimization problems can be modelled as mathematical programming [177] problems. There are 5 major subfields of mathematical programming, i.e. linear, convex, non-linear, dynamic and stochastic programming. Linear programming is the problem of maximizing/minimizing a linear function over a convex polyhedron. It can be solved via the simplex method i.e. solving a square system of equations after a number of variables equal to the degrees of freedom are given a fixed value. The fixed values can then be rotated until an optimum is found. Linear programming is a special case of convex programming, where the objective function and the inequality constraint are convex. The optimization based on convex programming is based on convergence of the considered values towards the highest local value. The fundamental property on top of which the convex programming reasoning is based is the equality of the local and global optimum. The optimization process involving non-linear objective functions and constraints is called non-linear programming. The key difference that non-linear programming brings in is the inequality between the local optimum and the global optimum i.e. there can be more global optimums and a simple "climbing uphill" algorithm cannot solve the optimization problem. Popular solutions for solving a non-linear programming problem are genetic algorithms, simulated annealing and the Monte Carlo method. The optimization of a set of subproblems in order to find an optimum for the global problem is called dynamic programming. It is based on the optimality principle that states: "In an optimal sequence of decisions or choices, each subsequence must also be optimal". Two approaches can be considered, i.e. a top-down approach, where the general problem is broken into subproblems being optimized in order to reach an optimum for the general problem, and a bottom – up approach, where all subproblems are envisioned in advance and larger problems are built up from their optimal solutions. Stochastic programming is an optimization process that incorporates probabilistic elements in the problem formulation. Possible solutions include a sampling method based on the Monte Carlo method, genetic algorithms and simulated annealing.

The game theory approach to the multi-objective optimization problem is based on the formulation of a game for the resource allocation problem. Fundamental concepts for the game theory approach are the Nash equilibrium and the Pareto optimality. More on game theory can be found in [177].

For further discussion on optimization problems related to wireless networking, see [178]-[180].

7.1.2 **Cross-layering**

An essential feature of the CRRM is the cross-layering approach. Cross-layering involves coordination between resources that conceptually belong to different layers within the layering architecture of the system. Implementing the cross-layering paradigm in the CRRM process is a difficult task since the concept can easily neglect the needed end-to-end network-wide scope. Three general cross-layer communication approaches are known [181]: signalling, function call method and local profiling. Since the function call method is operating system dependent (unsuitable for communication systems) and local profiling introduces significant complexity, delay and overhead, signalling is considered as most appropriate for cross-layer design for CRRM. There are several feasible design architectures for cross-layer signalling [182]. Interlayer signalling pipe is based on layer–to–layer propagation of signalling and data through the entire protocol stack (Figure 34). Top–bottom and bottom–top modes of operation are conceivable depending on the direction of the data flow.

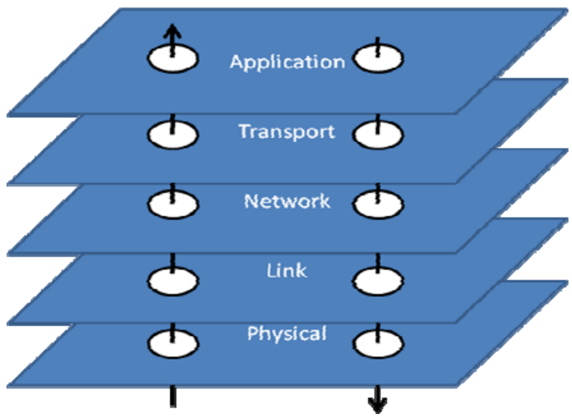


Figure 34: Interlayer signalling pipe [182].

An alternative approach is out of band signalization shortcuts. This direct interlayer communication strategy can be facilitated by the Internet control message protocol (ICMP) enabling message exchange between non-neighbouring layers (
Figure 35).

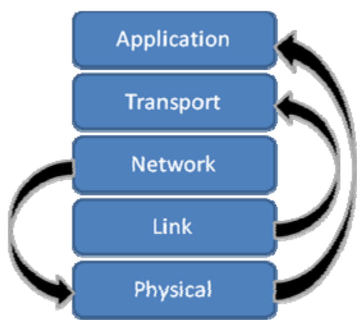


Figure 35: Direct interlayer communication [182].

The third option is a central cross-layer plane (Figure 36). This widely proposed signalling architecture is based on communication through specific interfaces between the separate layers and the central plane, which can be as simple as a shared database between the layers.

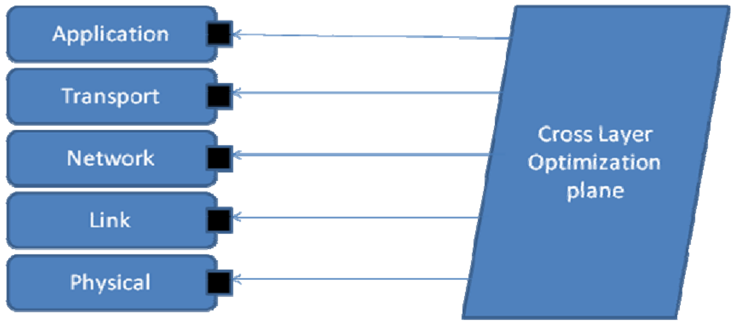


Figure 36: Central cross layer plane [182].

7.1.3 Learning

The learning process is paramount to achieving true cognition in resource management. A number of existing machine learning techniques are available for use to the cognitive resource management field. In general (though not required) they follow two stages of learning, i.e. training and inference making [177]. During the training phase, knowledge is built up from past experiences and in the inference making phase a deduction from the knowledge is inferred.

Machine learning algorithms can be broadly classified as: supervised, unsupervised and reinforcement machine learning algorithms [177]. The supervised learning uses training data that represents the inputs and their corresponding outputs. The idea is to achieve prediction capability for an output after a received input. Supervised learning can be implemented with a regression technique, where a single output is matched to a set of inputs, resulting in modelling of the output as a function of the inputs. An alternative approach is the classification technique based on minimizing the input misclassification to a wrong category of inputs (a single output is observed at first). The most complex (and most general) technique is the neural networks technique, which facilitates modelling of complex relationships between the inputs and the outputs.

Unlike supervised learning when both inputs and outputs are part of the training data, the unsupervised learning uses only input training data and assumes that the output is unknown. The idea is to detect a pattern between the inputs and constructing a structure of repeatable patterns. The most implemented method is clustering, where inputs are grouped into clusters based on their characteristics (e.g. *k*- means algorithm [177]).

The reasoning behind the reinforcement learning differs from the one used for the supervised and unsupervised learning. Reinforcement learning is not based on a-priori training data and therefore has no knowledge of the inputs and their respective outputs. Taking a long-term approach, the goal is deduced to maximizing the online performance. It creates a policy made up of a sequence of optimal actions in relation to the state of the environment for further utilization. Implementations of reinforcement machine learning algorithms include solutions based on dynamic programming, the Monte Carlo method as well as game theory approaches.

7.1.4 Reasoning

When realistically implementing CRRM, cross-layering, optimization and learning are all tightly connected and somewhat incomplete from a global point of view. This leads to the need for reasoning as the fourth feature for a full CRRM. Reasoning represents the actual decision on the resource allocation based on the optimal decisions from the cross – layering optimization process and knowledge from the learning process.

One way of implementing the reasoning component is through fuzzy logic. The fuzzy logic theory is based on mimicking simple human deduction instead of complex mathematical formulations [177]. Through reaching inference rules from simple fuzzy sets a number different kinds of system requirements can be reached. Fuzzy logic crosses the borders between optimization, learning and reasoning, as it can be applicable in all phases of the cognition process in a unique way.

7.1.5 CRRM architecture

From an architectural standpoint, cognitive resource management (especially when viewed through the dynamic spectrum access (DSA) prism) can be implemented in a centralized or distributed fashion [177]. The centralized CRRM is a continuation of the traditional RRM, where a central resource management entity manages the resources for the entire network. Every cognitive radio user sends data regarding its state and objective/requirement to this central controller. The centralized CRRM can be either optimization based or auction based. In the former approach the optimization problem is being formulated and solved, whereas in the latter approach different users submit bids containing relevant optimization data, after which an optimal solution is reached at the centralized controller. The distributed CRRM is increasingly gaining momentum lately, especially with the introduction of the IEEE 1900.4 standard [183]. In this case, each user collects exchanges and processes the information about the wireless environment independently and makes an autonomous decision. The user's behaviour during the management process can be described as cooperative, if the users cooperate trying to reach a network–wide objective, or non–cooperative, when they cooperate only for individual gain. Also, when the users interact exchanging information, they work in a collaborative manner, and when they do not interact at all and reach their decisions based only on self–acquired data, they operate in a non - collaborative manner. A summary of the interactions and behaviours is shown on Figure 37. This kind of approach has been proposed in [177] focusing primarily on dynamic spectrum access, but the same reasoning can be applied to CRRM in general. Reference [184] proposes a decentralized (distributed) approach to CRRM using an on-demand cognitive pilot channel (CPC).

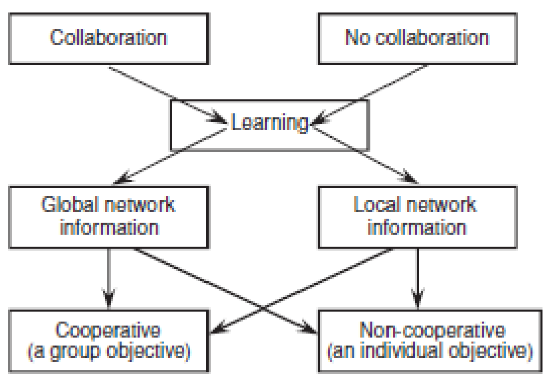


Figure 37: Distributed resource management [177].

The resource management rationalization developed for heterogeneous networks in general is applicable for cognitive radio networks [185]. The RRM can be viewed as a superset of the widely known joint radio resource management (JRRM) and the advanced spectrum management (ASM). The ASM is responsible for managing the spectrum allocation in a cognitive fashion, while the JRRM manages all other resources (e.g. power, modulation techniques used etc.).

7.1.6 Cognitive resource management implementations

Over the past few years a number of promising cognitive architectures have been proposed, but only a few have been actually implemented. Virginia Tech pioneered the work in the field of cognitive radios by developing the first cognitive engine prototype. Virginia Tech's prototype described in [186] presents a modularized structure within a general framework. The cognitive engine consists of the following key modules:

- *Environment modelling module*, responsible for environmental information collection;
- *Solution maker module*, that generates viable solutions based on knowledge from the knowledge base;

- *Multi-objective adaptive genetic algorithm* for situations with no memorized prior knowledge;
- *Knowledge database*;
- *Radio interface*, that interfaces the cognitive engine core;
- *Reconfigurable radio platform* and
- *User interface*, for connecting the user and policy domains with the cognitive engine's core.

University of Kansas [187] also uses the original Virginia Tech prototype for their own research. RWTH Aachen has developed a similar resource management entity called the Cognitive Resource Manager (CRM), [188]-[191]. The CRM follows a strict component based architecture consisting of a CRM core, generic interfaces, a distributed control and coordination module and a policy engine. Modularity is ensured within the CRM core through a certain level of abstraction, responsible for the definition of behaviours, action brokers and action resolvers. The behaviour components are the basic entity within the CRM core. A behaviour represents a framework for a single optimization problem, based on an input, processing and output mechanism. An action broker coordinates the coexistence of more behaviours and the action resolver represents the resolution method used by the action broker. The distributed control and coordination module enables the system to work in a distributed manner. The policy engine provides the policies, which restrict the operation to a set of static or dynamic constraints regarding the time and geographical location. The generic interfaces represent the interfaces between different layers and the CRM. Three generic interfaces are defined, i.e. ULLA for the physical and data link layer, GENI for the network and transport layer and CAPRI for the application layer. The CRM architecture is depicted in Figure 38.

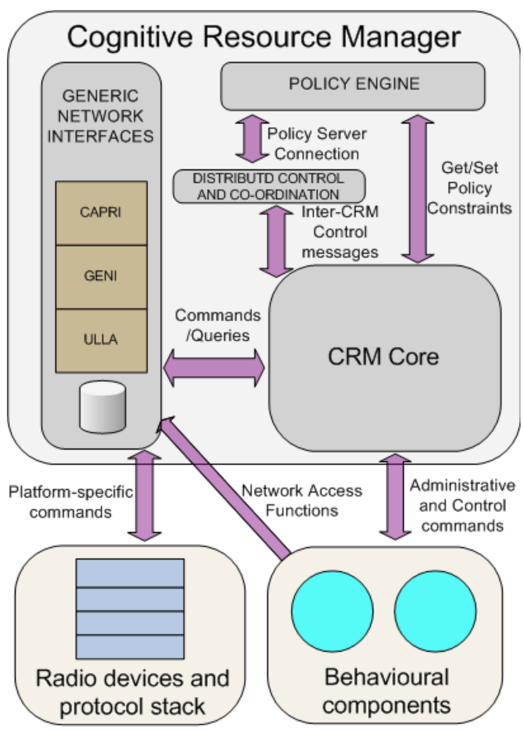


Figure 38: CRM architecture (from [188]).

Trinity College [192] presents another component based approach. A synergy of a reconfigurable node and cognitive engine is proposed as an architecture where all network stack layers are encapsulated as layers representing the layer component, whereas the reconfigurable software defined radio represents the radio component. Along these components specific interfaces are defined. The management of the reconfigurable node is carried out by a stack manager. The complete operation is assisted by the configuration parser, which acts as a translator between the network stack configuration and the stack manager, and the component manager that provides a set of services for the stack manager.

Reference [193] provides a study on the advantages of using cognitive resource management in future LTE systems. A context matching procedure based on the *k*-NN algorithm is proposed. Table 7.1 gives a comparison of key features among the prominent CRRM architectures today.

Table 7.1. Comparison of CRRM architectures

Feature	*Optimization*	*Cross – layering*	*Learning*	*Reasoning*
Virginia Tech [187]	Genetic algorithms	Only for layer 1-3	Reinforcement learning based	Case-based reasoning based on knowledge
RWTH Aachen [188]- [191]	Artificial intelligence algorithms	Through the entire stack via the CRM	Machine learning	Policy engine
Trinity Dublin [192]	Waterfilling	Yes, through layer components managed by a stack manager	No	N/A

7.2 *MAC protocols for CR Networks*

Spectrum access enables multiple CR users to share the spectrum resource by determining who will access the channel or when a user accesses the channel. In order to have efficient non-colliding spectrum usage, different MAC procedures have been developed. The MAC schemes can be sorted as random, time slotted or hybrid. Random access and time slotted schemes may be used in infrastructure-based networks. On the other hand, maintaining network-wide time synchronization in mobile ad hoc networks is difficult and is infeasible to adopt completely slotted protocols in those scenarios [194].

Random access protocols: The MAC protocols in this class are generally based on the Collision Sense Multiple Access with Collision Avoidance (CSMA/CA) principle and they do not need time synchronization. Here, the CR user monitors the spectrum band to detect when there is no transmission from other CR users and transmits after a backoff time in order to avoid simultaneous transmissions.

Time slotted protocols: These MAC protocols need network-wide synchronization, where time is divided into slots for both the control channel and the data transmission.

Hybrid protocols: These protocols are a combination of the random and time slotted protocols. The control signalling generally occurs over synchronized time slots. However, the data transmissions may have random channel access schemes, without time synchronization. In a different approach, the durations for control and data transfer may have predefined durations constituting a superframe that is common to all the users in the network. The access to the channel may be completely random within each control or data duration

Next, we discuss CR MAC protocols [194] and classify existing approaches based on the network architecture (infrastructure-based and ad-hoc) and channel access schemes (random access, time slotted, and hybrid), as shown in Figure 39.

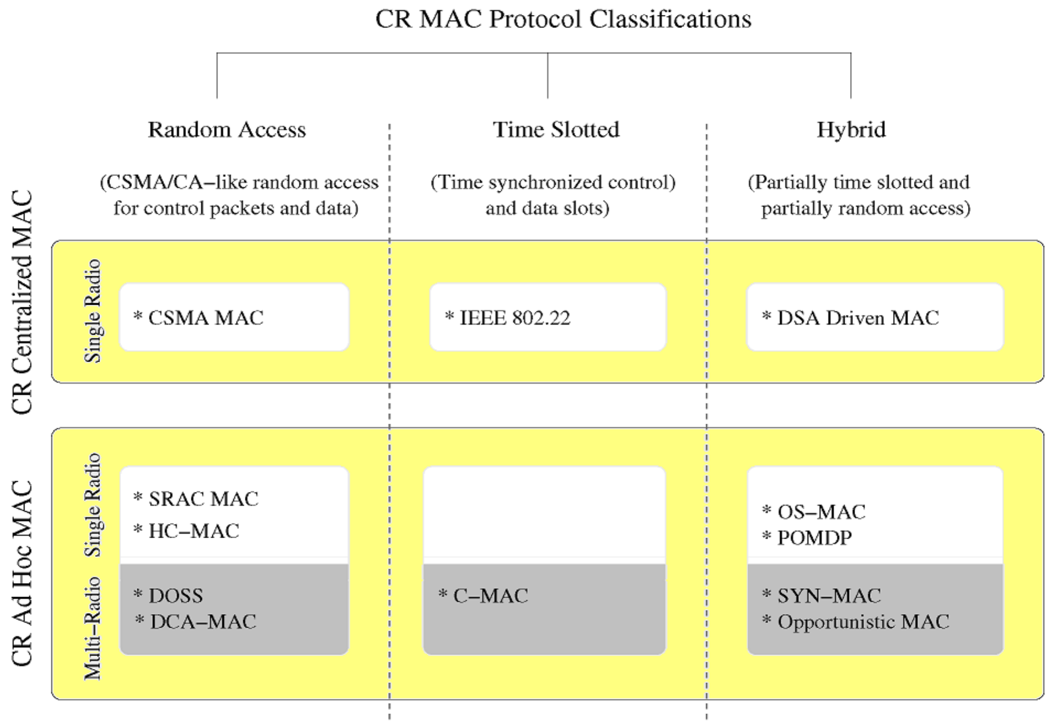


Figure 39: Classification of CR MAC protocols [194].

7.3 *MAC protocols for CR Infrastructure-based Networks*

The MAC protocols for infrastructure-based networks need a central entity, such as a base station, that manages network activities, synchronizes and coordinates operations among nodes. This centralized architecture helps in the coordination among the CR users for collecting the information about the network environment, and allows the spectrum decisions to be localized. The existing works can be divided into three channel access schemes: random access, time-slotted behaviour, and a hybrid approach that partially combines both of the previous two.

7.3.1 Random Access Protocols

A CSMA based protocol is proposed in [195] that uses a single transceiver and in-band signalling. This protocol ensures co-existence among the CR users and the PUs by adapting the transmission power and rate of the CR network. The CR users and the PUs, having overlapping coverage areas, establish direct single-hop connections with their respective base stations. The proposed MAC protocol allows simultaneous transmission of the CR users even when the PUs are detected, as long as the interference caused to them is contained within a pre-decided threshold.

The operation of the protocol is as follows: The primary network follows classical CSMA, in which the PU undertakes carrier sensing for period τ_p before sending a request-to-send (RTS) packet to its base station. The primary base station may reply with the clear-to-send (CTS) if it is available for the data transaction. However, the CR users have a longer carrier sensing time (τ_s, where $\tau_s >> \tau_p$) so that priority of spectrum access is given to the PUs. Based on the (i) distance of the CR users from the CR base station, and the (ii) noise power, the base station decides the transmission parameters, namely the transmit power and data rate, for the current transfer. The CR user is allowed to send just one packet in one round of this negotiation in order to minimize the risk of interference to the other PUs.

While coexistence is important, a significant interaction between the CR and the primary networks is implicitly assumed. The CR base station and users cannot determine if the PUs experience multiple failed transmission attempts without feedback from the primary network. Moreover, the transmission power for the CR users is only partitioned into two discrete levels (low or high) that does not reliably protect the PUs for all possible topologies. Moreover there is no clear assignment of the transmit power, coding scheme, transmission rate to the CR users, especially considering the interdependencies that exist in these parameters.

7.3.2 Time Slotted Protocols

IEEE 802.22 is a centralized standard that uses base stations for spectrum access and sharing [196], [197]. The base station manages its own cell and all associated consumer premise equipments (CPE) or CR users in this case. In the downstream (DS) direction, 802.22 MAC uses Time Division Multiplexing, while in the upstream (US) direction, demand assigned TDMA is utilized. The standard specifies time-slotted operation with the frame hierarchy. At the apex, a *superframe* is defined, each of which is composed of multiple MAC *frames* preceded by the frame preamble. The MAC frame is formed by two parts in the frame structure: DS subframe and US subframe.

The key features of the IEEE 802.22 standard are (i) extensive support for spectrum sensing, (ii) spectrum recovery, and (iii) coexistence of the different users. To reduce the spectrum sensing time, the protocol has a two-stage sensing (TSS) mechanism: fast sensing and fine sensing. Fast sensing is completed quickly to identify the frequency band for subsequent fine sensing while fine sensing is performed on-demand. This allows CR networks to meet the strict quality of service (QoS) requirements by making a tradeoff between improving the sensing accuracy and maximizing the transmission time. For spectrum recovery, the incumbent detection recovery protocol (IDRP) is used to enable the network to restore normal operation with minimal performance degradation. Finally, for the coexistence of users in CR networks, the beacons in coexistence beacon protocol (CBP) carry information about the cells and the DS/US bandwidth allocations for the users. This scheme for inter-base station communication allows the base stations to exchange information in priority over the general data traffic of the CR users.

7.3.3 Hybrid Protocols

In hybrid protocols the data transfer occurs in pre-determined time slots, while the control signalling uses random access scheme. A game theoretic DSA is proposed [198]. Moreover, this MAC is cluster based and the game policy in each cluster is managed by a central entity within the cluster. The proposed MAC protocol has high spectrum utilization, collision free spectrum access with QoS and fairness guarantees. There are 4 integral components in the DSA-driven MAC framework, as shown on Figure 40: DSA algorithm, clustering algorithm, negotiation mechanism and collision avoidance mechanism. Each of these functions is described in the following text.

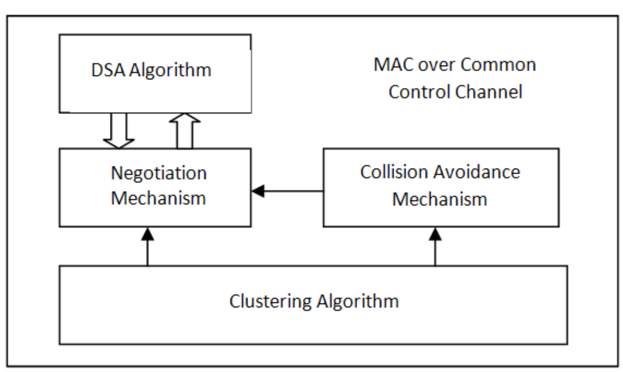


Figure 40: DSA driven MAC framework [198].

DSA algorithm. The game theoretic DSA algorithm aims at pursuing a global optimization solution by reaching the Nash Equilibrium. In particular, the CR user behaviour can be modelled as a repeated game model Γ= (N,S_i,u_i,T), where N is the set of players, S_i is the strategy of player i, u_i is the local utility function of player i and T is the decision timing for the game. All the players update their strategy in order to maximize their own local utility function until the game converges to the NE. When a NE is achieved, a collision free channel access can be established. The utility function is composed of two components, i.e. the payoff or the gain obtained from the choice of the strategy and the price the player should pay to the others for its strategy. The utility function may also take into account QoS and fairness requirement.

*Clustering algorithm***.** The nodes are organized in clusters. Each cluster has a unique identity, depending on the position. When a node enters the network, it can choose which cluster to join, based on the smallest distance from the cluster center. After joining a cluster, the node broadcasts with maximum power its coordinates and the cluster ID, so that all the other nodes within other clusters are aware of topology changes. A Virtual Header (VH) is used, which is a packet unique to the cluster that also carries a token. The token contains the updated player list. The beginning of the game starts when the token starts to move from one user to another, and it terminates when the token stops.

*Negotiation mechanism***.** The negotiation mechanism is illustrated in Figure 41. The mechanism deals with the control message exchange and coordination of the actions of the CR users. This negotiation occurs over a Common Control Channel (CCC) and is composed of two phases, i.e. inquiry stage and formal negotiation stage. The inquiry stage comprises the process of identifying nodes that wish to start data communication. After that, the nodes will become quasi-game players and will be considered in the formal negotiation stage.

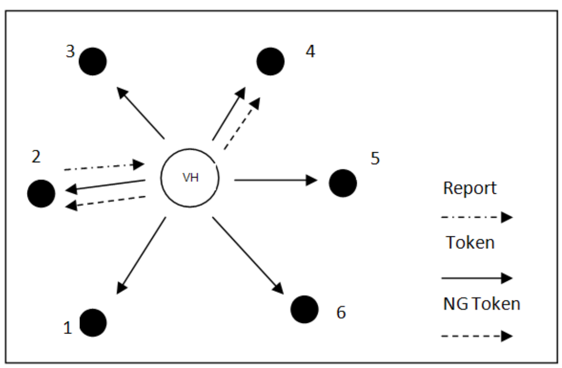


Figure 41: Negotiation process in the DSA–MAC [198].

When a node wants to start a new transmission, it sends a report packet to the VH node. This would mean start of the inquiry stage. The players will start building their player set game. Then, the VH is passed to the first player in the player set and the formal negotiation stage can start. The VH now carries the negotiation (NG) token which contains the dynamic game information required by the game players. In this way, the game players can update their local strategy and the related information in the NG token. The NG token is then passed to the next player in the list. The formal negotiation stage ends when the game converges to the NE. Specifically, Figure 41 depicts a situation when node 2 wants to start a transmission and reports the request to the VH node. During the inquiry stage a token inquires all the cluster members, but only nodes 2 and 4 want to transmit. Then, the formal negotiation stage is carried out in order to coordinate nodes 2 and 4 to process the formal game.

*Collision avoidance mechanism***.** This mechanism is intended to ensure avoidance of collisions during negotiation state in different clusters. Out-of-band busy tones are used for this purpose. Two different types of busy tones are exploited, i.e. *inside-cluster* and *outside-cluster* busy tones. Inside-cluster busy tone is set up by a node receiving a message, in order to prevent other nodes from other clusters to interfere with the negotiation. Outside-cluster busy tone is set up by a node overhearing messages from other clusters in order to avoid initiating a new round of negotiation within the cluster, as it may result in interference.

The time and the number of iterations taken to converge to the NE may be prohibitively large. Moreover, the proposed scheme does not provide sensing support, however it assumes it. The protocol is characterized with low scalability as the negotiation delay increases with the number of players. The difficulty in maintaining synchronization and possible collisions in the game information packets are some of the other factors that affect the protocol performance [194].

In [199] an On-demand Cognitive Pilot Channel (CPC) scheme is proposed. It divides the coverage area into meshes with each mesh consisting of a CPC transmitter and many secondary users. The CPC transmitter operates on a special channel called the cognitive pilot channel (CPC). The CPC is assumed to be universally available to any secondary user which is tuned to it. The cognitive pilot channel (CPC) may carry information like mesh location information, operators, available radio access technologies (RAT) within the mesh and available channels. The basic idea is to provide spectrum allocation details on the CPC based on the demand (or requests) from the secondary users.

7.4 *MAC Protocols for CR Ad-hoc Networks*

These protocols do not have a central entity for the operation of the network. Though the resulting architecture is scalable and has flexible deployment, the distributed spectrum sensing, sharing and access necessitate increased cooperation with the neighbouring nodes. Maintaining time synchronization throughout the network and obtaining the information from surrounding nodes with minimum overhead are some of the factors that must be considered in the protocol design.

7.4.1 Random Access Protocols

This class of protocols is specially suited for ad hoc networks. Some of these protocols have support for multiple radio transceivers [147], [200], while others use a single radio [103], [201].

Dynamic Open spectrum Sharing (DOSS) MAC: Most of the works assume that a set of fixed non-overlapping spectrum bands are given, and a node can use only one of them at a time. However, if nodes are allowed to dynamically combine the available bands, it will result in better network performance. The Dynamic Open Spectrum Sharing (DOSS) MAC protocol provides an innovative solution to address the hidden node and exposed node problem [147]. Three radios are assigned distinctly to the control, data and busy-tone band, respectively. The spectrum bands used for data transfer are mapped to the frequencies in the busy tone band. Thus, whenever a node transmits or receives data on a given channel, it also emits a busy signal in the corresponding busy tone band.

Apart from avoiding intra-CR network interference, we believe that this solution can also be applied to coordinate the MAC layer sensing. A node may sense on the channel which does not have a corresponding busy tone, thereby ensuring that the transmission of the other CR users are not mistaken for the PU activity.

The main drawback of this protocol is the use of separate and out-of-band spectrum for issuing the busy tones and for the CCC. Thus, the spectrum is not efficiently utilized. Moreover, the need for multiple transceivers is not justified as two of them are not used for data communication at all.

Distributed Channel Assignment (DCA) based MAC: A simple extension of the IEEE 802.11 CSMA/CA protocol using distributed channel assignment (DCA) is proposed in [200]. It uses multiple transceivers, with a dedicated out-of-band CCC for signalling. In addition, the proposed protocol also utilizes spectrum pooling which helps to enhance spectral efficiency by reliably detecting the primary network activity, thus serving as physical layer signalling.

The use of a separate CCC results in wastage of the spectrum and may also become the bottleneck on the link. Moreover, there is no specific support for spectrum sensing or PU related adaptation that is required for CR networks. A variant of this protocol uses a single transceiver that alternates between monitoring the CCC and the data spectrum bands.

Single-Radio Adaptive Channel MAC (SRAC) Protocol: The single-radio adaptive channel (SRAC) algorithm is proposed in [201] that adaptively combines spectrum bands based on the CR user requirement, called as *dynamic channelization*. In addition, it uses a frequency division multiplexing (FDM)-like scheme, called as *cross-channel communication*, in which a CR user may transmit packets on one spectrum band but receive messages on another.

However, this work does not completely address the means to detect the presence of a jammer and distinguish malicious activity from legitimate network conditions. Though this approach uses a single radio, it will result in significant *deaf* periods, where control messages not sent on the receive spectrum band of the node will not be monitored. Moreover, the signalling overhead for maintaining updated receive spectrum bands of all the neighbours continuously adds to the traffic.

Hardware Constrained MAC (HC-MAC): The Hardware-Constrained MAC [103] protocol aims at efficient spectrum sensing and spectrum access by considering the hardware constraints, such as, the operational limitations of a single radio, partial spectrum sensing, and spectrum aggregation limits. It uses a CCC, but also has a single radio that simplifies the hardware requirements.

Hardware constraints can be divided into two classes given by (i) sensing constraints and (ii) transmission constraints. The sensing constraints concern the tradeoff between time taken for sensing and the resulting accuracy. As an example for *fine* sensing, a larger proportion of time needs to be allocated per channel, and hence a limited portion of the spectrum may be scanned. On the other hand, the transmission constraints are related to the limitations posed by the orthogonal frequency division multiplexing (OFDM) that decides the bandwidth range, as well as the maximum allowed number of the subcarriers.

A key difference of this protocol as against the previous work is that the sensing at either ends of the link is initiated *after* a pair of CR users wins the contention on the dedicated CCC. However, the control messages used for channel negotiation may not be received by the neighbouring nodes if they are engaged in their own data transfers. Moreover, the number of control messages is significant and may saturation the control channel earlier than classical single channel RTS-CTS based MAC protocols.

7.4.2 Time Slotted Protocols

Cognitive MAC (C-MAC): The synchronized and time slotted cognitive MAC (C-MAC) [202] protocol is aimed at higher aggregate link throughput and robustness to spectrum change using multiple transceivers. C-MAC includes two key concepts: the rendezvous channel (RC), and the backup channel (BC). The RC is selected as the channel that can be used for the longest time throughout the network, without interruption among all other available choices. It is used for node coordination, PU detection, as well as multi-channel resource reservation. The BC, determined by out-of-band measurements, is used to immediately provide a choice of alternate spectrum bands in case of the appearance of a PU.

In C-MAC, each spectrum band has recurring *superframes* composed of a beacon period (BP) and a data transfer period (DTP). The RC is used on a network-wide communication, neighbour discovery, and sharing of load information for each band. Moreover, this is also used to exchange the schedules for the BP, so that the beacons are not simultaneously sent over all the spectrum bands. Upon power-up, each CR user scans all the available spectrum bands to determine the vacant spectrum resource. In these bands, if it hears a beacon, then it may choose to join that specific band and also set the global RC to the band specified in the beacon.

The main drawbacks of C-MAC are the following: All the beacons sent by the CR users must be accommodated in the BP of a superframe, which results in low scalability. Moreover, it is expected that the RC converges to a constant spectrum band over time, which cannot be guaranteed in distributed networks. Moreover, the spectrum switching is not instantaneous - the information must first be disseminated to the other CR users in the beacon period of the RC. It is unclear how the non-overlapping nature of the BPs and the quiet periods are enforced without the presence of a central entity.

The limits associated with the use of a RC are circumvented by the distributed slotted protocol proposed in [80], which provides in-band signalling through a dedicated control window in addition to the beacon and the data transfer periods. Furthermore, during this window, the bridge nodes are allowed to use multiple channels, i.e., to access more than one coordination group in each superframe for optimizing the performance.

Integer Linear Programming (ILP) based MAC protocol: In [203], the MAC layer scheduling problem was formulated as an integer linear programming (ILP) problem to solve the issue of spectrum allocation. The MAC layer schedule assigns a unique channel and time slot pair to every outgoing link of the nodes in the network ensuring that two nodes do not transmit on the same channel at the same time. The number of nodes is fixed and each node is given a unique identity. The nodes were assumed to have GPS functionalities for time synchronization.

Dual channel communication scheme: The dual unlicensed band MAC (DUB-MAC) [204] uses two channels for its operation. The channels are referred to as signalling and control band (SCB) and data transmission band (DTB). The SCB (located in the GSM band) is used as a control channel while the DTB may be located in any primary user spectrum and used as data channels.

7.4.3 Hybrid Protocols

Opportunistic Spectrum MAC (OS-MAC): The OS-MAC protocol uses pre-determined window periods for coordinating the choice of spectrum among the CR users and exchanging control information to separate the latter intro groups [205]. However, within each window, the spectrum access is random, and hence this is a hybrid protocol.

The spectrum bands used for data communication are considered to be non-overlapping and a separate CCC is assumed for exchanging control packets between users on different bands. It uses a single radio that needs to switch between the data band the CCC.

The OS-MAC protocol has several drawbacks. The membership of the CR users to the clusters is based on the assumption that each user already knows which cluster to join. As the clusters are formed based on group-communication needs, this is infeasible without exchanging detailed cluster information. Moreover, as the CR delegate does not coordinate with the other clusters for efficient spectrum sensing, as each cluster operates independently without enforcing silent periods. Moreover, there is no consideration of protection to the PUs either by adapting transmission, power control, among others.

Partially Observable Markov Decision Process (POMDP) based MAC: A partially slotted single-radio MAC protocol based on the theory of partially observable Markov decision process (POMDP) is proposed in [80]. A similar approach is also used in the cognitive radio access scheme in [206], where limited sensing capabilities of the cognitive radio imply that only one channel can be sensed at a time. In this case the system is also classified as partially observable and the analysis becomes involved.

The approach adopted in [80] integrates the design of spectrum access protocols at the MAC layer with spectrum sensing at the physical layer and traffic statistics determined by the application layer. The two main issues addressed are: (i) joint consideration of the spectrum sensing and spectrum access issues, and (ii) transmitter-receiver synchronization, i.e. ensuring that both the transmitter and receiver hop in the spectrum together without additional control overhead. The time is divided into slots, and in each slot the spectrum access follows a sensing-RTS-CTS-DATA-ACK schedule.

The POMDP is a generalization of a Markov decision process and is addressed as partial because the network state cannot be fully observed due to partial spectrum sensing or due to sensing error. Here, time is divided into slots, and at the start of each slot, the protocol decides a set of spectrum bands for sensing, and another set of bands for transmission. These decisions are made with the aim of maximizing the throughput of the CR user while limiting the interference to the PUs and exploiting the past history of the spectrum band. During transmission, classical CSMA is assumed.

The theoretical basis for the proposed MAC protocol assumes that the spectrum usage statistics remain unchanged for several time slots. As a result of this, the PU activity *pattern* is learnt over time and the protocol is strongly affected with frequent and random spectrum changes. Moreover, the optimal result is reached after very large time durations, and the protocol does not perform well in the initial stage.

Synchronized MAC (SYN-MAC): The SYN-MAC protocol proposed in [207] does not need a CCC but has a dedicated radio for listening on the channel for control messages. A second transceiver is used for data traffic.

The main idea of the protocol is the following: Time is divided into time slots and each slot represents a particular data channel. The control signal exchange occurs in the channels represented by the slots while the data transfer can occur in any channel that is found suitable between a given node pair. Thus, the control signalling is similar to slow frequency hopping, in which the channel is switched periodically. At the beginning of each time slot, the CR users tune their dedicated control radios to the channel specified by it, and the users that wish to initiate a data transfer send out a beacon at this time. Interested neighbours respond with their own list of available channels, and further communication is carried out in one of those selected channels.

The above protocol has the advantage of not using a dedicated CCC, and the dedicated listening also addresses the multichannel hidden terminal problem. However, this approach does not guarantee protection to the PUs, as their arrivals are notified only unspecific time slots to the neighbours. In addition, the channel may not be utilized efficiently, as it can be used only once in a given cycle.

Opportunistic MAC: The opportunistic cognitive MAC protocol proposed in [208] uses two transceivers, one for a dedicated CCC, and the other that can be dynamically tuned to any chosen spectrum. The time is slotted for the data transfer over the licensed channels, while the CCC operation is partly slotted, followed by a random access negotiation phase. Thus, it is a hybrid protocol.

To ensure that all the channels are sensed, each CR user independently chooses a channel with equal probability. If sufficient number of CR users is present, then all the channels can be covered with high probability. Moreover, the authors provide a detailed analytical treatment of the average number of channels available to the CR users, and the upper bound on their throughput.

Apart from the overhead of maintaining the time synchronization and the need of multiple transceivers, this work does not specify the exact link layer interactions between the nodes. As an example, multiple transmissions may be possible at the same time between different node-pairs that may affect the sensing results. As the channel for sensing is randomly chosen, the neighbouring nodes do not have a priori knowledge of this event and do not silence their own transmissions to improve the sensing accuracy.

7.5 *CR MAC Protocol Challenges*

7.5.1 Control Channel Design

The spectrum access involves control signalling between the two CR users on either ends of the link. This messaging must be uninterrupted by the neighbouring PU activity as it is used to exchange the sensing information, and coordinate the channel access. For this, reliable and dynamically changing control channels must be devised.

7.5.2 Adapting to PU Transmission

Some PUs have specific transmission patterns, such as pre-determined spectrum usage times and durations, such as television broadcast stations, or may have occasional random access to the channel, such as public service agencies. At these times, the CR MAC protocol may infer the nature of the PU and adapt its own transmission to avoid both interference to itself and also prevent conflict with the PUs. For this reason, dynamic power control and transmission scheduling schemes need to be devised.

7.5.3 Evolution and Learning

The occupancy history of the spectrum bands by the PUs may vary with the time of the day and location. It is desired that the MAC protocol learns the characteristic PU activity and accordingly alters its spectrum selection and data transmission strategy.

Although the POMDP MAC protocol proposed in [80], takes the initial steps in this direction, more detailed and elaborate learning models are needed. How long should the learning duration be and its effect during the network operation, are issues that need to be investigated. Moreover, the problem of constructing detailed channel occupancy needs further research, so that the different times of the day and different locations traversed by the mobile CR user can be incorporated. The probabilistic spectrum selection algorithm that uses this history may be designed to guarantee performance bounds during long-term operation. For this, open challenges include how the theoretical research and network operation are combined, so that the gains arising from the choice of the spectrum at the link layer are appropriately weighted in each decision round, and the computational time for considering the past history is minimized.

7.5.4 REM enabled Radio Resource Management

The context information that will be included in the Radio Environment Maps will offer opportunities for more efficient allocation of the available radio resources among the users (having either legacy or cognitive terminals) within a composite wireless network. The challenge that lies ahead is related to the actual exploitation of the REM context data (e.g. related to PHY measurements, power profiles, topological data, RAN lists, directional spectrum sensing data, measured interference etc.) for the development of cognitive RRM/MAC algorithms (either extending some of those previously analyzed or proposing new schemes). These schemes may be dealing with both intra-layer and cross-layer parameters' selection, and will account for a balance between power and bandwidth efficiency. The metrics for assessing those schemes have to be related to both the performance enhancements that they will provide (in terms of user and system throughput efficiency and capacity utilization) and the actual complexity that they will require (in terms of signalling overhead, storage needs etc).

8 Testbeds and Platforms, Measurements, and Empirical Models

The emerging of new wireless technologies and the trend towards wireless broadband systems arise the spectrum scarcity problem lately. Regulatory agencies have issued licenses for different radio spectrum bands to various services and several measurement campaigns have been set up in order to evaluate spectrum usage. The results clearly show that numerous bands are vacant. Therefore, Dynamic Spectrum Access (DSA) has been proposed in order to alleviate this problem and increase the spectral utilization. However, in order to understand and predict primary users' activity and to build appropriate models of spectral and environmental utilization, detailed spectral measurements are needed. Precise decision on measurement methods and data analysis is a step towards more efficient opportunistic DSA. In this Section we provide an overview of the measurement campaigns carried out, and spectrum models that have been developed based on the data obtained. We shall also discuss at the end of the Section some of the key CR prototyping platforms and testbeds that can be used as a foundation for prototyping activities further on in the project.

8.1 *Measurements*

Different projects and research campaigns have different goals varying from generic analysis of spectral use to specific individual technologies. This section shortly reviews several spectrum measurement testbeds, elaborates on the hardware requirements, parameters and measurement methods as well as on the analysis of the empirical results

8.1.1 Measurement challenges

Different systems have different characteristics in terms of operating frequencies, channel bandwidth, transmit power etc. Selection of a particular wireless system for spectrum measurement, such as any cellular communication system, would lead to a decision for specific sensing equipment. The most appropriate measurement method for spectrum utilization is the *real-time monitoring*. Unfortunately, only a fraction of the current equipment on the market operates with real-time sensing. Therefore, this method is under-interrogated and not suitable for practical purposes. The usual practical method today would be the *sweep sensing* method in which one portion of the band is monitored at a time and each frequency component of a signal is sampled sequentially in time [209]. Swept-tuned measurements are differentiated by the sampling rate. More sophisticated and expensive signal analyzers have higher sampling rates and, thus, can collect higher amount of signal characteristics like modulation, coding and even the information itself [210]. This type of signal detection is known as *feature detection* [211]. Measurements done with smaller sampling rates undersample the signals and cannot achieve feature detection. In this case, the method of *energy detection* can be applied to the gathered data. Energy detection method senses the pure signal power in the particular portion of frequency band and compares it with a predefined limit for primary user indication. This method lacks detailed signal information and cannot make differentiation between primary user signals, interference and noise. Another method that should enable this differentiation is the *cyclostationary detection* method which uses the cyclostationarity inherently present in wireless signals (e.g. the mean value and the autocorrelation function change periodically as functions of time). This method can extract signals in the background of noise and interference. Finally, short signals in time domain correspond to broad signal bandwidth, so the swept method of operation might not sweep through the complete bandwidth, i.e. might miss short primary user transmissions.

Future research and improvement could also be done in detection of weak signal levels. Basic signal analyzing equipment might not satisfy measurement sensitiveness of few selected technologies. Examples are spread spectrum technologies which expand signal's spectrum in order to operate at very low signal-to-noise levels.

8.1.2 **Previous Measurements**

The first larger scale spectrum use measurement campaign has been performed in the USA by National Telecommunications & Information Administration (NTIA) regulator between 1995 and 1998 [212]. Its main goal was to inspect spectrum utilization differences between several locations in the USA. The results indicate large differences mainly caused by geographic differences.

Another measurement campaign, also considered as a reference campaign in papers and literature due to its extensive coverage and early date, is carried by the Shared Spectrum Company (SSC) as a part of a National Science Foundation (NSF) grant [213], [214]. It is actually the first measurement campaign in the context of DSA [211], carried in the USA from January 2004 to August 2006. The SSC campaign shows that urban and rural locations differ in spectrum usage and one should take different measurement access in both areas. Figure 42 depicts a summary of SSC measurement results. Spectrum occupancy metric is given by the percentage of time in which spectrum has been found occupied. The figure clearly shows that a considerable amount of radio spectrum is underutilized.

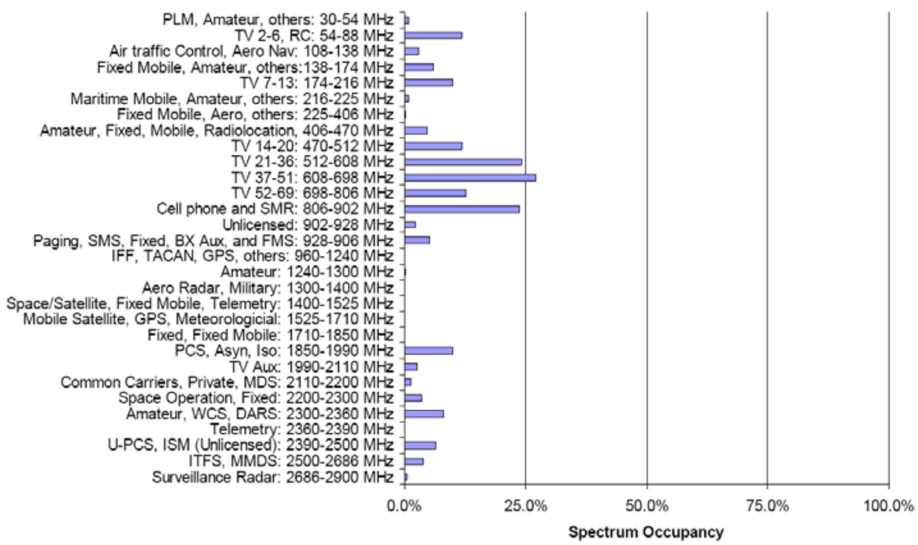


Figure 42: Summary of Shared Spectrum Company measurements at six different (urban/rural) locations [211], [215].

Similar measurements have been conducted in different projects, varying from wide-ranging cognitive radio testbeds to specific technologies evaluation. Examples are VT-CORNET [216], Aachen measurement campaign [217], Football World Cup 2006 in Germany, UPC measurement campaign [218], [219], Singapore measurement campaign [220] etc. VT-CORNET is a Cognitive Radio Network Testbed developed by Wireless @ Virginia Tech research center with emphasis on heterogonous wireless communication. Aachen's spectrum occupancy measurement campaign [221] is a good reference campaign due to broad inspected frequency band and measurement goals. UPC measurement campaign [218], [219] performs a detailed evaluation of spectrum occupancy over a very broad frequency range up to 7 GHz, in a band-by-band basis and making use of a carefully designed measurement setup and rigorous evaluation methodology, in order to indentify frequency bands of potential interest for the future deployment of the DSA technology. Singapore's measurements inspect possible opportunistic use of spectrum holes and represent base for future long term studies. Additionally, specific technologies or events have been examined in FIFA 2006 world cup in Germany. Namely, cellular networks behaviour in time periods around football matches have been of specific interest [211], [222], [223].

Following sections elaborate in more details these measurement campaigns, along with measurement setups and comparison of different used measurement parameters.

8.1.3 Review of previous measurement setups

In this Section we review some illustrative examples of past measurement campaigns, carried out by different research groups.

8.1.3.1 Aachen measurement campaign

One of Aachen measurement campaign's major goals was to investigate spectrum usage over longer time scales of multiple days to few weeks. Five different locations were included in the measurement process, where four of them were in Germany and the fifth one was in the Netherlands. The measurements in this campaign included spectrum sensing in the 20 MHz – 6 GHz frequency range where most wireless services work today. Wireless systems have different characteristics in terms of used bandwidth, transmit power, multiple access scheme etc. yielding the need to optimize the measurement parameters for a particular technology. However, Aachen measurement campaign inspects different technologies in parallel with partially suboptimal measurement configuration. The main band is divided in four sub-bands, each 1.5 GHz wide with a resolution bandwidth of 200 kHz. The detailed set of used measurement parameters is listed in Table 5.1. The chosen frequency resolution is suited well for new technologies with greater bandwidth per channel parameters. However, it is not fine enough to differentiate very narrowband primary user signals.
Three different antennas were used, each specifically selected for a certain frequency band, as follows:

- AOR DA-5000 discone antenna (20 MHz – 1.52 GHz)
- AOR DA-5000JA smaller discone antenna (1.5 GHz – 3 GHz)
- AG KS 1-10 antenna of type *Antennentechnik Bad Blankenburg* specified up to 10 GHz (3 - 6 GHz)

The selection of antennas avoids the need for further reconfiguration of the measurement setup to cover all possible directions. Namely, the antennas are vertically polarized with omnidirectional characteristic in the horizontal plane. The measurement setup also comprises a high performance spectrum analyzer Agilent E4440A [224], which supports up to 8192 measurement points. In order to enable sufficiently sensitive measurements, the received signals are preamplified using the inbuilt preamplifier in the spectrum analyzer for frequencies bellow 3 GHz and an external preamplifier for frequencies above 3 GHz.

Table 5.1. Spectrum analyzer configuration used [217]

Center frequency	Band 1: f_c = 770 MHz Band 2: f_c = 2250 MHz Band 3: f_c = 3750 MHz Band 4: f_c = 5250 MHz
Frequency span Resolution bandwidth Number of measurement points	1500 200 kHz 8192
Sweep time Measurement duration	1s About 7 days per sub-band
Detector type Preamplifier	Average detector Up to 3 GHz: 28 dB gain Above 3 GHz: none or ≥ 24 dB gain
Instrument Typical DANL (displayed average noise level)	Agilent E4440A spectrum analyzer -169 dBm At 1 GHz and 1 Hz resolution bandwidth

The sweep time of 1s is chosen as a compromise between the amount of data that is collected throughout one week of measurement, the variance of the gathered samples due to noise variation and the sampling frequency. Taking into account that the spectrum analyzer periodically realigns the internal calibration and pauses the measurement for few seconds, a measurement of one week results in a trace of about 335000 sweeps. On average, each sweep takes 1.8s and 1000 sweeps take about 30 minutes.

The measurement process is controlled and configured using a standard laptop. Flexibility in measurement configuration as well as quick access to analysis and visualization results is done with high-level MATLAB software. Finally, all components mentioned above are placed in a weather-proof RF-shielded box, as depicted on Figure 43.

Figure 43: The measurement setup placed on a building roof [217].

8.1.3.2 UPC measurement campaign

The main objective of the UPC measurement campaign is to characterize the spectrum occupancy in the range from 75 MHz to 7075 MHz assuming both indoor and outdoor scenarios in urban and suburban locations in Barcelona, Spain. The measurement configuration employed in this work (see Figure 44) relies on a spectrum analyzer setup where different external devices have been added in order to improve the detection capabilities and hence obtain more accurate and reliable results. The design is composed of two broadband discone-type antennas covering the frequency range from 75 to 7075 MHz, a Single-Pole Double-Throw (SPDT) switch to select the desired antenna, several filters to remove undesired overloading (FM) and out-of-band signals, a low-noise preamplifier to enhance the overall sensitivity and thus the ability to detect weak signals, and a high performance handheld spectrum analyzer (Anritsu Spectrum Master MS2721B) to record the spectral activity. The spectrum analyzer was controlled by a laptop connected via a cross-over Ethernet cable. This measurement setup was carefully designed taking into account the findings of the study performed in [225].

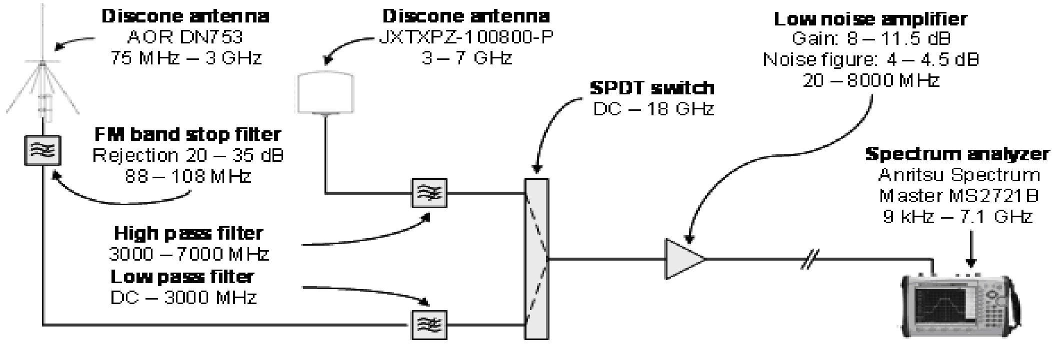


Figure 44: Measurement setup employed in the UPC measurement campaign.

The main configuration parameters used for the spectrum analyzer are shown in Table 5.2. . The measured frequency range (75-7075 MHz) is divided into 25 blocks with variable sizes ranging from 45 MHz up to 600 MHz, depending, among others, on the regulatory spectrum allocations (to guarantee that no allocated spectrum band is split off when measuring), and the Resolution BandWidth (RBW), which is close related to the bandwidth of the signal being measured. The frequency bands defined in these studies are measured 1, 24 or 48 hours, depending on the measurement location (the 7-day measurement period is being employed in some ongoing measurements). When the circumstances allowed unattended operation (e.g., inside the university premises), a 24- or 48-hour measurement period was selected. In public or similar places, where the presence of an operative was required, measurement periods of 24/48 hours were infeasible and were therefore shortened to 1 hour. See reference [225] for details. The measured traces were saved in an external storage device and post-processed off-line using MATLAB in a powerful PC.

Table 5.2. Spectrum analyzer configuration used [218]

	Parameter	Value	
Frequency	Frequency range	75-3000 MHz	3000-7075 MHz
	Frequency span	45-600 MHz	
	Frequency bin	81.8-1090.9 kHz	
	Resolution BandWidth (RBW)	10 kHz	
	Video BandWidth (VBW)	10 kHz	
Time	Measurement period	1/24/48 hours / 7 days	
	Sweep time	Auto	
Amplitude	Built-in pre-amplifier	Deactivated	Activated
	Reference level	-20 dBm	-50 dBm
	Reference level offset	0 dB	-20 dB
	Scale	10 dB/division	
	Input attenuation	0 dB	
	Detection type	Average RMS detector	

The measurement equipment of Figure 44 was employed to perform empirical measurements of various spectrum bands throughout the UPC university campus in an urban environment. This strategic location enabled to accurately measure the spectral activity of, among others, a TV repeater, a FM broadcast station, several nearby base stations for cellular mobile communications and a military headquarter as well as some potential maritime transmitters due to the relative proximity to the Barcelona's harbour. The different considered geographical locations are illustrated in Figure 45 and include both indoor (1) and outdoor environments at high points (2), narrow streets (3–7), between buildings (8– 10) and in open areas (11–12). The considered measurement locations represent various physical scenarios of practical interest and embrace a wide range of receiving conditions and levels of radio propagation blocking, ranging from direct line of sight to severely blocked and faded signals. This variety of measurement conditions enabled to observe the same set of transmitters under different propagation conditions and with different levels of Signal-to-Noise Ratio (SNR). This wide range of considered measurement locations gives us an idea of the available spectrum opportunities and the perception of secondary users moving along different practical scenarios within an urban environment with different levels of radio propagation blocking.

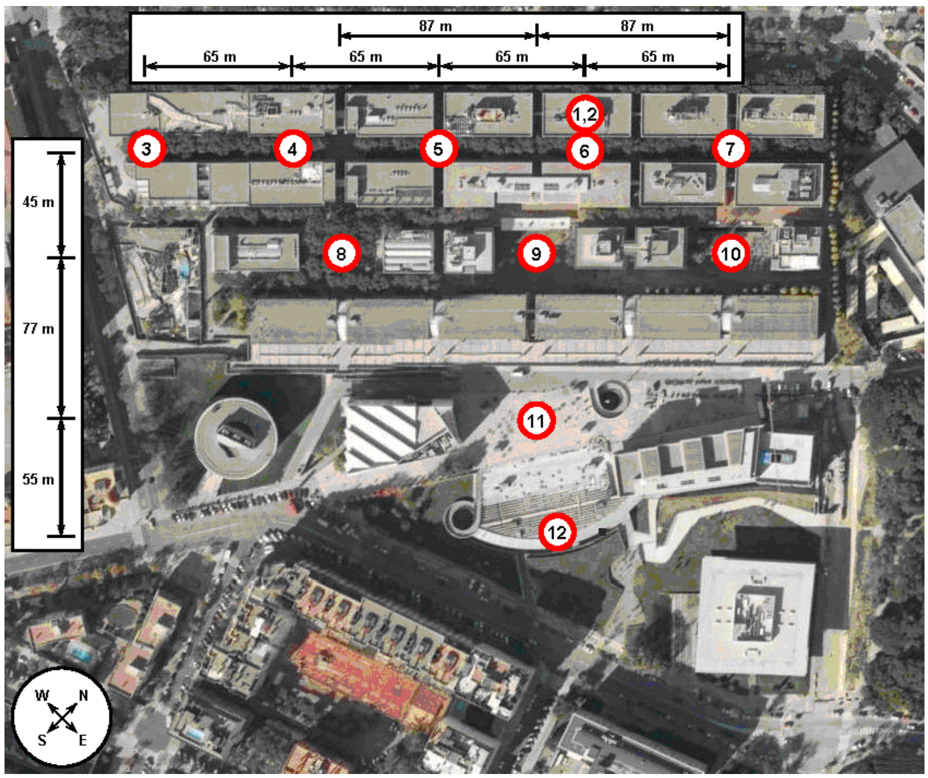


Figure 45: Measurement locations considered in the UPC measurement campaign.

8.1.3.3 *Singapore measurement campaign*

Singapore measurement campaign observes a 24-hour spectrum usage in frequency bands ranging from 80 MHz to 5850 MHz during 12 weekday periods. Its objectives are to find how radio spectrum is utilized and to identify bands for future opportunistic secondary user access. Employed equipment uses energy detection methodology, i.e. measures the amount of spectrum detected and compares it with a certain power threshold. More detailed description about primary user detection, measurement analysis and threshold setting is given in the section of empirical results and analysis.

The measurement has been taken on a single location, on a roof top of a building. The core element in the setup is the Agilent's spectrum analyzer of model E4470B [226], with operating frequency range of 9 kHz to 40 GHz, measurement range from -150 dBm to 30 dBm, ±1 dB overall amplitude accuracy and a maximum sensitivity of -150 dBm. The spectrum analyzer is connected to BiConiLog (hybrid biconical and log periodic) directional antenna of model 3149 by ETS-Lindgren

[228], with frequency range of 80 MHz to 6 GHz. Since detection with uniform angle distribution requires an omni-directional antenna (like in Aachen's testbed), the BiConiLog antenna is rotated manually every day by 30^0. Moreover, additional signal amplifying is done by the spectrum analyzer's internal amplifier. The spectrum analyzer is controlled remotely by LabView8.2 software installed on a desktop computer. The analyzer and the computer are connected using General Purpose Interface Bus (GPIB). All components are placed in a cabinet with ventilation.

The overall frequency range of 5770 MHz (80 MHz – 5850 MHz) is divided into several 60 MHz bands, consisted of 401 measurement points. Each 60 MHz block is measured every 13.8 minutes that would sum up a total of 104 received data samples daily or 1248 samples for the whole 12-day measurement campaign. All configuration parameters are shown in Table 5.3.

Table 5.3. Spectrum analyzer configuration parameters [229]

Inspected bandwidth Frequency span Frequency (measurement) points Resolution bandwidth Sweep time	80 kHz – 5850 MHz 60 MHz (97.5 blocks x 60 MHz = 5850 MHz) 401 (in 60 MHz block, 13.8 min per block) 150 kHz (2.064 sec each, 1248 samples per point) 2.064 sec
Measurement duration	12 days
Video bandwidth	100 kHz
Instrument Typical DANL (displayed average noise level) Antenna	Agilent E4407B (9 kHz – 40 GHz) -150 dBm BiConiLog 3149 (hybrid biconal, log periodic)

8.1.3.4 *Spectrum Observatories*

In addition to specific measurement campaigns, there have been recent activities in the research community towards setting up specific *spectrum observatories*. The objective of these setups is to provide continuous stream of spectrum measurement data over a large period of time, although at present gathered from only a small number of measurement locations. One of the first proposals towards such as setup has been given in [230]. Recently, the researchers at the Worcester Polytechnic Institute have also set up a spectrum observatory, which has also been made publicly accessible through a web interface [231].

8.1.4 **Methodological aspects**

Although previous spectrum measurement campaigns followed similar approaches, they employed different evaluation methodologies. The use of a common and appropriate evaluation methodology in previous studies would be desirable not only to prevent inaccurate results but also to enable the direct comparison of results from different sources. In this context, [225] presented a comprehensive and in-depth discussion of several important methodological aspects to be accounted for when evaluating spectrum occupancy, providing a quantitative evaluation of the impact of different factors on the obtained results as well as various useful guidelines. The results presented in

[225] highlighted the importance of carefully designing an appropriate methodology when evaluating spectrum occupancy in the context of CR. This section summarizes the main points discussed in [225].

8.1.4.1 Design of the measurement setup

There are many factors that need to be considered when defining a strategy to meet a particular radio spectrum occupancy measurement need. As detailed in [226], there are some basic dimensions that every spectrum occupancy measurement strategy should clearly specify, namely *frequency* (frequency span and frequency points to be measured), *location* (measurement site selection), *direction* (antenna pointing angle), *polarization* (receiving antenna polarization) and *time* (sampling rate and measurement period). The measurement setup employed in the evaluation of spectrum occupancy should be designed taking into account the previous factors since they play a key role in the accuracy of the obtained results. The measurement setup should be able to detect, over a wide range of frequencies, a large number of transmitters of the most diverse nature, from narrow band to wide band systems and from weak signals received near the noise floor to strong signals that may overload the receiving system. Each one of the employed components should therefore be selected carefully.

One of the key components is the selected antenna. When covering small frequency ranges or specific licensed bands a single antenna may suffice. However, in broadband spectrum measurements two or more broadband antennas may be required. Most of spectrum measurement campaigns are based on omni-directional measurements in order to detect primary signals coming for any directions. To this end, omni-directional vertically polarized antennas are the most common choice (e.g., discone-type). Even though some transmitters are horizontally polarized, they usually are high-power stations (e.g., TV stations) that can still be detected with vertically polarized antennas. Directive antennas (e.g., log-periodic antennas) may be used in order to improve the system's sensitivity at the cost of increased measurement complexity (more measurements are required in order to cover the entire 360-degree range of azimuths).

Another important aspect is amplification, which improves the system's sensitivity. As shown in [225], if the measurement setup is not sensitive enough, the occupancy statistics may be subject to high estimation errors, thus leading to wrong conclusions on primary activity and spectrum usage. Moreover, [225] also shows that amplification by itself is not enough: an appropriate amplification configuration is required in order to accurately estimate spectrum usage. It is worth noting that choosing an amplifier with the highest possible gain not always is the best option in broadband spectrum surveys, where very different signal levels may be present. The existing tradeoff between sensitivity and dynamic range must be taken into account. To choose the correct preamplifier, we must look at our measurement needs. If we want absolutely the best sensitivity and are not concerned about measurement range, we would choose a high-gain, low noise pre-amplifier. If we want better sensitivity but cannot afford to give up any measurement range, we must choose a lower-gain pre-amplifier. A reasonable design criterion is to guarantee that the received signals lie within the overall system's Spurious-Free Dynamic Range (SFDR). As explained in [225], if the SFDR is not taken into account, spurs caused by strong signals might arise above the system's noise floor and they would be detected as signals in truly unoccupied bands, thus resulting in inaccurate results and erroneous conclusions on the spectrum occupancy. Band stop filters to remove undesired strong signals as well as low/high pass filters to remove out-of-band frequencies can help to satisfy the required SFDR without any loss in sensitivity at other frequencies.

8.1.4.2 Frequency and time dimensions

In spectrum measurements, the entire measured frequency range needs to be divided into smaller frequency blocks in order to improve several aspects of the measurements such as frequency resolution, etc. As suggested in [225], a reasonable option is to divide the frequency range in wide spectrum blocks (e.g., 500-1500 MHz) and perform measurements in order to obtain a first picture of which spectrum bands are occupied. Based on this first impression and following the local spectrum allocations, the entire frequency range can then be divided into smaller bands in such a way that higher frequency resolutions are obtained in those bands where some activity was detected and/or the bandwidth of the transmitted signals is narrower.

The relation between the bandwidth of measured signals and frequency resolution is an important aspect to be accounted for. As pointed out in [225], if the frequency bin (i.e., the separation between two consecutive measured frequency points) is larger than the bandwidth of the signal being measured, spectrum occupancy is notably overestimated. On the other hand, occupancy estimation is reasonably accurate as long as the frequency bin size remains acceptably narrower than the signal bandwidth. Another aspect related to the frequency dimension is the Resolution BandWidth (RBW) of the spectral measurements. Narrowing the RBW increases the system's ability to resolve signals in frequency and decreases the noise floor, which in turn improves the ability to detect weak signals but at the cost of increased measurement time. A RBW of 10 kHz in modern spectrum analyzers was proven in [225] to be an adequate tradeoff between detection capability and measurement time.

The time dimension of the spectrum measurements is defined by two parameters, namely the sampling rate, i.e. the rate at which PSD samples are recorded, and the measurement period. While the former is constrained (and in some cases automatically adjusted) by the measurement device, the latter can be easily controlled. Very different measurement periods have been considered in previous measurements ranging from a few minutes to several days. From a statistical viewpoint, the question is how long spectrum bands should be measured in order to obtain a representative estimate of the actual spectrum usage in such bands. Based on the discussion provided in [225], a reasonable option to obtain representative results without any a priori information of the band to be measured is to consider measurement periods of at least 24 hours in order not to underestimate or overestimate the occupancy of frequency bands with some temporal patterns. Although a 24-hour measurement period can be regarded as adequate, it is certainly true that a relatively large number of recorded traces and thus reasonably long measurement periods are required to correctly characterize the primary activity of allocated spectrum bands. For example, 48-hour periods would provide more realistic estimates. Moreover, 7-day periods would also include the potentially different usage patterns of some spectrum bands in weekdays and weekends. A 24-hour measurement period properly chosen can be considered as a reasonable tradeoff between reliability of the obtained results and time required to complete the measurement campaign.

8.1.4.3 Data post-processing

Regardless of the final measurement campaign objective, one of the very first steps of data post-processing is to determine which captured PSD samples correspond to occupied and unoccupied channels. If only power measurements of the spectrum utilization are available, the energy detection method is the only possibility left. Due to its simplicity and relevance to the processing of power measurements, energy detection has been a preferred approach for many past spectrum studies. Energy detection compares the received signal energy in a certain frequency band to a predefined threshold. If the signal lies above the threshold the band is declared to be occupied by the primary network. Otherwise the band is supposed to be idle. Therefore, the measured PSD samples need to be compared to a threshold in order to determine whether they correspond to occupied channels or not.

The decision threshold is a critical parameter in data post-processing since its value severely impacts the obtained occupancy statistics. High decision thresholds may result in underestimation of the actual spectrum occupancy due to the misdetection of faded primary signals. On the other hand, excessively low decision thresholds may result in overestimation caused by noise samples above the threshold. As shown in Figure 46, different systems may exhibit different sensitivities to the variation of the decision threshold. In general, the duty cycle for high-powered transmitters such as TV stations and cellular communication base stations (downlink direction) shows a lower decreasing rate as the decision threshold increases. On the other hand, for bands where the received signal levels are lower the duty cycle is more sensitive to the decision threshold, with changes from 100% to 0% in 5 dB or less. This observation highlights the importance of using an adequate criterion to select the decision threshold.

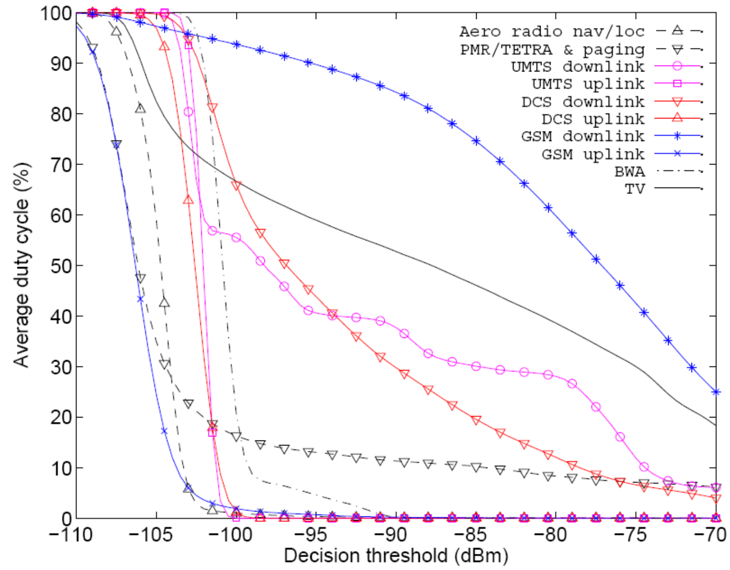


Figure 46: Average duty cycle as a function of the energy decision threshold for various systems (from [225]).

In [225], various methods for selecting the decision threshold were analyzed and evaluated comparatively. To this end, the same set of empirical data was post-processed based on the energy detection principle but using various criteria to select the decision threshold, including:

- MaxNoise criterion: Selects the maximum noise level recorded at each measured frequency point as the decision threshold. This option guarantees that no noise sample lies above the threshold and therefore that spectrum occupancy is never overestimated. However, occupancy may be underestimated due to weak signal samples lying below the maximum noise level.
- m-dB criterion: Fixes the decision threshold *m* decibels above the average noise level. The main drawback of this method is that the noise variance and also the maximum noise level may vary band-by-band depending on several measurement configurations. Therefore, a constant *m*-dB threshold over the entire measurement range may not be appropriate.
- PFA criterion: Based on a target Probability of False Alarm (PFA) for a CR network equal to P_{fa}, the decision threshold at each measured frequency point is fixed such that only a fraction P_{fa} of the measured noise samples (replacing the antenna with a matched load) lies above the threshold. This approach conciliates the previous criteria.

These methods assume a perfect knowledge of noise properties, at least of the mean, minimum and maximum noise levels, which can be easily measured by simply replacing the antenna of the measurement equipment with a matched load. To avoid wrong occupancy results in noisy environments where the ambient noise is higher than the measurement equipment's noise floor, the resulting thresholds obtained with these methods need first to be compared and validated with the noise level obtained when connecting again the antenna and measuring unoccupied spectrum bands. The study performed in [225] concluded that the PFA criterion (with P_{fa}=1%) can be considered as a reasonable trade-off between improvement in the ability to detect weak signals and overestimation errors in bands occupied by high-power transmitters. Regarding the *m*-dB criterion, the experiments in [225] demonstrated that a constant value of *m* over the entire measurement range failed to provide consistent results.

8.1.5 **Empirical results and analysis**

8.1.5.1 Duty cycle modelling

Duty cycle appears to be one of the most important parameter in threshold setup in standard energy detection scenarios. It is defined as the fraction of time that a signal spends above a certain threshold [220], [232]. This section presents a stochastic model of the distribution of the duty cycle based on a 200 kHz channelization used in [217].

Due to measurements of multiple different frequency bands allocated to various wireless systems, a generic energy detection scheme is applied based on a threshold γ. Different threshold values are used in order to address different background noise levels and achieve realistic estimates of the duty cycle. For 200 kHz channels the lowest threshold is γ = -107 dBm, given earlier in the requirements document of the IEEE 802.22 standardization committee [217], [233]. Three different threshold values are evaluated: γ = [-100, -95, -90] dBm/200 kHz.

Let $\Omega_{t,i}$ denote the spectrum occupancy at time t and channel i, defined to be one, if the received PSD (power spectral density) measured at time *t*, channel *i* exceeds the threshold γ, and zero otherwise. The duty cycle for a channel *i* can be computed as follows

$$DC_i = \frac{\sum_{t=1}^{N_i} \Omega_{t,i}}{N_i} \quad , \tag{5.2}$$

where N_i is the number of measured samples per channel.

In order to find the distribution of DC_i over all channels *i*, a Cumulative Distribution Function (CDF) is estimated using kernel-based methods as offered by MATLAB. Afterwards, the PDF is computed by simple differencing. Figure 47 shows a few selected examples for the CDF. The slope for the very low and very high duty cycle is highest indicating that these cases are most probable. According to the Aachen research team from [217], this result is not only valid for the shown frequency bands but for nearly all investigated technologies and frequency bands.

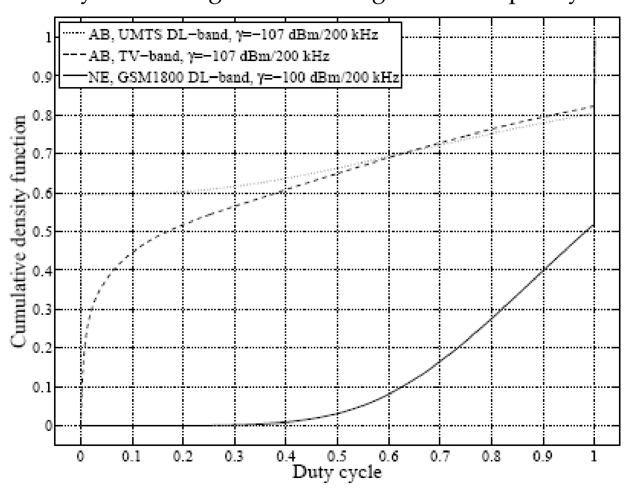


Figure 47: Comparison of different duty cycle distributions using appropriate thresholds [217].

These two extremes can be explained by the fact that very often not a single sample passes the detection threshold resulting in $DC_i \equiv 0$, whereas a strong continuous signal such as broadcasting stations results in $DC_i \equiv 1$. Also, some technology characteristics increase these probabilities. For example, the UMTS technology based on Code Division Multiple Access (CDMA) uses continuous signals in the downlink direction. Unused UMTS channels result in $DC_i \equiv 0$ and Aachen measurements show a 60% usage of the UMTS band. This is the reason for very flat UMTS graph in the area of low duty cycles.

The shown GSM1800 graph is an example of a very busy band without vacant channels. Some of the channels might still be vacant, but strong noise samples trigger false detections. Distributions for high probabilities for the two extremes $DC_i \cong 0$ and $DC_i \cong 1$ can usually be modelled with the beta distribution. Since the beta distribution does never approach 0 or 1, a modified beta distribution for duty cycle modelling is used. For details, see [217].

Since Aachen measurement campaign does not model each wireless system separately, a single and general model for the duty cycle was needed. The modified beta distribution can be used as a good model for the duty cycle distribution, i.e. the generality of the proposed model outweighs the model imperfections. To show this, the symmetric version of Kullback-Leibler divergence is used and results are depicted on Figure 48. All fits are sufficiently close to the measured distribution and prove that the modified beta distribution can reproduce the measurement characteristics of the duty cycle.

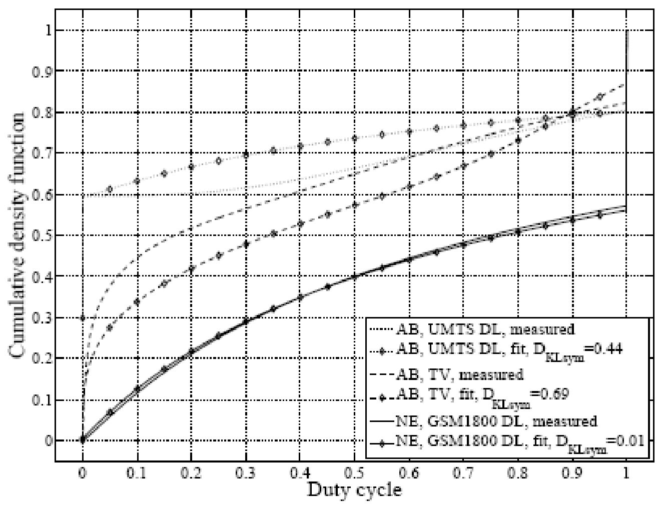


Figure 48: A comparison of different duty cycle distributions and the corresponding modified beta distribution fits (thresholds are same as used on Figure 47 [217]).

The presented duty cycle model is beneficial for multiple applications in the evaluation of DSA systems. Examples are algorithms for adaptive sensing or dynamic assignment of secondary users to vacant channels.

8.1.5.2 Energy detection threshold setup

Spectrum occupancy is the most often used metric to determine which frequency bands are occupied and which are free. A way to define the occupancy is the event that the received signal strength at the measuring equipment is above a certain threshold. However, choosing the threshold is quite critical for opportunistic use of an unoccupied licensed channel. Very low threshold would result in a very conservative occupancy estimate that indicates a busy channel due to the presence of ambient noise and make the opportunistic use limited. On the other hand, if the threshold is chosen too high, some channels may be declared as unoccupied even though some devices are operating perfectly well at low power with highly sensitive receivers.

Aside from the accuracy of the model described in the previous subsection, different energy detection thresholds still result in significantly different distributions but, based on measurement data, interference and primary user signals cannot be differentiated. This fact leaves the need to choose a detection threshold arbitrarily based on an estimation of the background noise floor [174]. In some cases, like [234] and [217]-[221] the detection threshold is determined by comparison to the noise distribution as measured with 50 Ω fitted match. Such proposition would not work in noisy environments, resulting in $DC_i = 1$ for numerous channels. The threshold estimation can be based on the PDF of the received PSD samples. Using a threshold proposed by IEEE 802.22 standardization committee and inspecting a calm radio environment in [217], the background noise process is weak enough such that all detected signals are due to intended primary user transmissions instead of unintended interference.

According to theory and existing literature on spectrum survey, the threshold should be set a certain dB above the noise level of the measurement equipment itself. The negative aspect of this method is that if the ambient noise is lower than the equipment noise, the threshold is set too high and primary user's signal levels belonging in the interval between equipment and ambient noise would not be detected. This method is prone to the sensitivity of the measurement equipment. To avoid this, the threshold can be set a certain dB above the ambient noise. One of ITU recommendations ([223], page 168) suggests a threshold 10 dB above the ambient noise. Anyway, ambient noise is hard to determine in practice, although its theoretical value can be calculated easily. In the case of [234] the noise level of the measurement equipment is a little higher than the theoretical ambient noise. It was decided to use a threshold of 6 dB above the minimum received signal power recorded in an observed band during 24 hours over 12 days.

Figure 49 shows the spectrum occupancy using 3 subplots for the Singapore measurement campaign. The upper subplot shows the maximum received power versus frequency. The maximum receiver power is determined by the maximal received sample at that frequency point during the 12 day measurement period. The middle subplot shows the spectrum occupancy versus time and frequency. The occupancy is determined as follows. Each frequency point has 104 daily samples in the corresponding example and the maximal sample of all 12 day period samples is compared with the threshold. In case of a higher value a red dot is displayed in the corresponding place in the plot. The lower subplot shows the duty cycle over frequency.

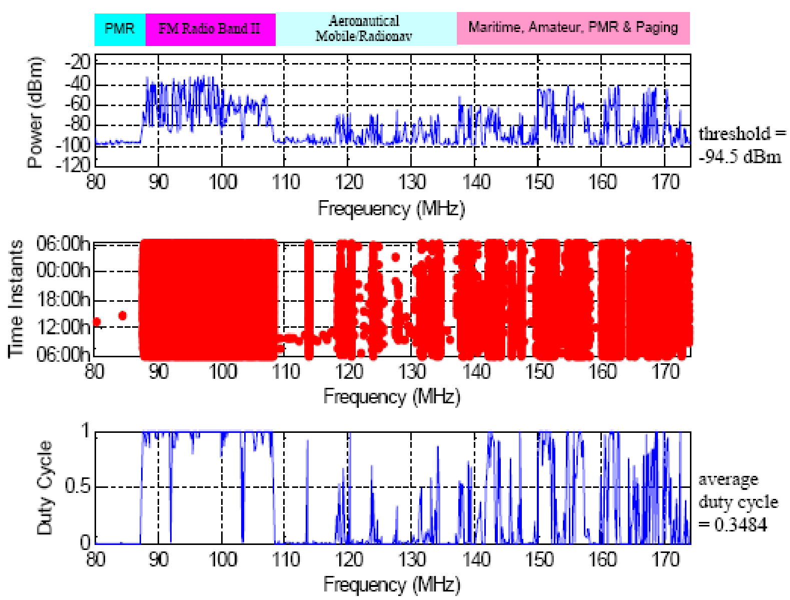


Figure 49: Maximum receiver power, spectrum occupancy and duty cycle display [220].

8.2 *Platforms and Testbeds*

There exists a high level of heterogeneity in the design of practical CR networks. We characterize testbeds in the following way based on the devices used, communication system, and level of heterogeneity [235]:

- *Accessibility:* The overhead, both in terms of the material and manpower required for a thorough experimental evaluation, is often a detrimental factor in building testbeds. Several institutions provide external interfaces, where the individual devices of the testbed can be programmed by a user remotely, often over the Internet. We refer to this as open access, and strongly advocate this as the best strategy for undertaking reproducible results. Moreover, this approach extends support to the research community that can make use of an existing investment in infrastructure.

- *Device Hardware:* There are commercially available device types, as well as custom designs that may support (i) varying number of transceivers, (ii) processors clocked at different instructions/per second, (iii) frequency ranges and bandwidth that are supported by these transceivers, (iv) antenna types, among others. Ideally, the testbed should be highly re-configurable in terms of dynamic spectrum selection, and be able for wide-band sensing over large ranges.

- *Scale:* Depending upon the resource constraints, testbeds vary in the number of nodes. Our survey points to a large variation, ranging from around a dozen to nearly 50 nodes. Specifically, large testbeds allow for realistic testing of the effect of the interference caused by intra-CR network transmissions on licensed user detection, and the performance of spectrum sharing in the detected vacant bands.

- *Heterogeneity:* Most of the existing testbeds are composed of homogenous devices, and each node has similar communication and processing capabilities. However, real-world networks are likely to be highly diversified in these respects. Hence, devising a compatibility plane is needed, where individual nodes offer additional and often distinct capability over a minimum acceptable feature set. Such testbeds may also be used to test the coexistence of CR networks managed by different entities in a common spectrum pool.

- *Protocol Support:* Given the high degree of reconfigurability in the CR devices, developing a user modifiable protocol stack that can run on the devices is a challenge. When research efforts are undertaken at each layer, basic implementations of the other protocols layers, not in the scope of the work, must be present. As an example, TCP implementations over CR may rely on spectrum sensing information from the physical layer. Moreover, the basic structure should be easily modifiable, as there has been an increasing trend towards developing cross-layer techniques that integrate and utilize the complete spectrum as well as network information.

8.2.1 Typical CR Platform Architecture

In this section, we describe the architecture of a CR device, discuss the key component blocks, and the factors that determine their design choices. As illustrated in Figure 50 typical existing platforms are based on a split architecture, where a reconfigurable generic radio device is connected to a host, typically a desktop or laptop computer. The key resource allocation and digital signal processing (DSP) operations are undertaken on the host, which is connected to the CR device through a high-speed connection (e.g., USB or Gigabit Ethernet). The host contains implementation of the communication protocol stack, which handles data at the packet level, and of the physical layer (PHY) functionalities. The output of the processing on the host is a digital sample stream that is transferred to the CR device for further processing. Reconfigurable Board: A typical CR device consists of a motherboard with plug-in transceivers that permit incoming radio-frequency (RF) signals to be digitized and generates outgoing RF signals from the digital sample stream sent by the host computer. The platform typically includes an embedded field-programmable gate array (FPGA), allowing processing in hardware of the samples on the ingress and egress paths. Interchangeable daughterboards can cover different frequency ranges. Digital/Analog conversion is realized either on the FPGA, or on dedicated hardware. For example, the Universal Software Radio Peripheral 2 (USRP2), which will be described in detail in subsection 5.6, mounts a specialized 400MS/s 14- bit digital-to-analog converter (DAC), and 100MS/s 16-bit analog-to-digital converter (ADC).

A soft-core processor may be implemented on the FPGA to handle internal board operations, e.g., controlling arbitration on the data bus. For example, in USRP2 a 32-bit soft-core processor (AeMB) is implemented on the FPGA and handles most of the internal USRP2 operation. Note that in the basic USRP2 configuration, the AeMB does not perform any DSP functions; these are done purely in software in the DSP RX and TX pipelines on the host. Additionally, a CR platform will embed fast access memory (in the order of a few Mbytes), which can be implemented on the FPGA itself; and larger low-cost memory for long-term storage, for example through an external SD card.

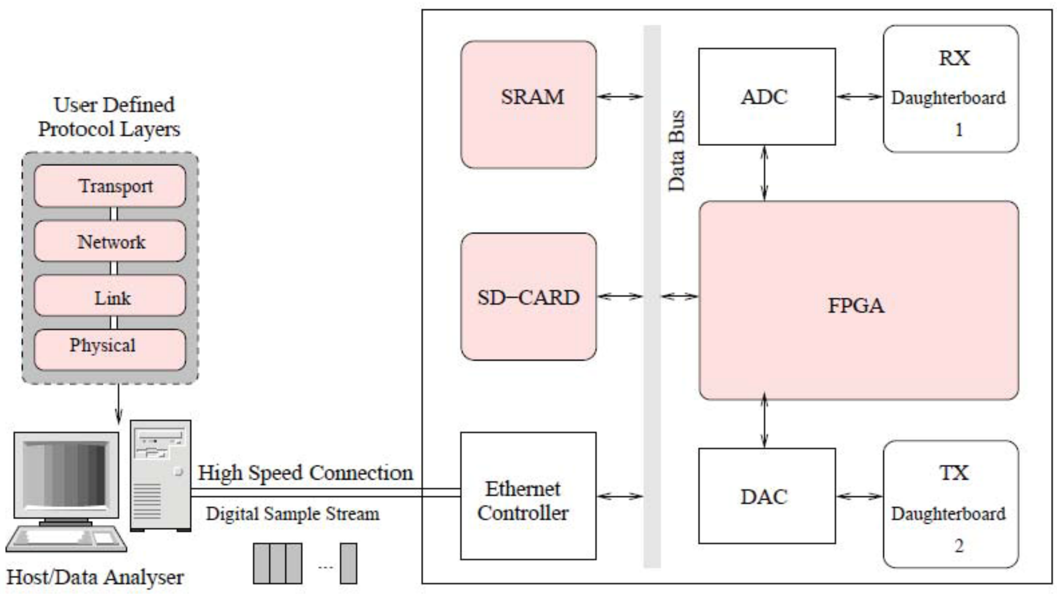


Figure 50: Internal organization of a CR node (from [235]).

8.2.2 BEE2

The Berkeley Emulation Engine 2 (BEE2) is a multi-purpose, reusable, modular and scalable framework for computationally intensive problems [237]. Among the several applications of the BEE2 framework, the implementation of Software Defined Radio (SDR) functionalities for cognitive spectral reuse and their evaluation in a testbed are BEE2 target domains [238]. The BEE2 hardware architecture is based on a DSP and computational board (the compute module) and on a modular RF front-end. The BEE2 software is based on a virtual file system embedded into a standard Linux OS kernel. Libraries based on Simulink environment are provided to the testbed user for script coding and for the programming of hardware processes on the BEE2 equipment.

The BEE2 software is based on the BORPH Operative System which extends a standard Linux kernel to include support for FPGAs. Instead of treating FPGAs as coprocessors, BORPH treats FPGAs in the system as normal computational resources, relying on the concept of hardware process. This behaviour is realized through the Input/Output Register (IOREG) virtual file system, which encapsulates conventional memory mapped I/O concept with a virtual file system. From the software point of view, IOREG registers manifest themselves as special virtual files automatically created by the BORPH kernel and based on information embedded in a BORPH Object File (BOF). Executing a

BOF file causes the kernel to configure FPGA's as needed according to the BOF file. The use of a Linux kernel as Operative System enables the native support for virtually any standard Linux software.

The BEE2 can be programmed using Matlab/Simulink coupled with the Xilinx system generator. The tool chain is augmented with BWRC developed automation tools for mapping high level block diagrams and state machine specifications to FPGA configurations. Hardware designs are first created in Simulink environment using block libraries provided by Xilinx System Generator. Simulations are then performed within Simulink to verify basic operations of the design including BORPH specific blocks. Subsequently, a set of fully automatic Matlab scripts is run in order to generate a BOF, which embeds all information needed to program and communicate with a FPGA during run-time. BOFs can be created to control the Compute Module user FPGA, the Compute Module control FPGA or the front-end FPGA.

In [239], an experimental setup based on the BEE2 equipment is described. The testbed implements CR functionalities in the unlicensed 2.4 GHz band in indoor environments. This spectrum band is unlicensed, so the cognitive radio operation in this band is not subject to an agreement with licensed users. Furthermore, it is considered as a very crowded spectrum with many unlicensed devices that are not able to intelligently control and avoid mutual interference. Commercially available WLAN devices for 2.4 GHz band, such as IEEE 802.11 B/G cards, can be easily used for primary user emulation. The BEE2 infrastructure supports multiple connections of laptop cards and 2.4 GHz front-ends that can be combined as a cognitive radio system capable of sensing and transmission.

In [238], the BEE2 testbed is deployed for the study of CR spectrum sensing algorithms. An Agilent signal generator is used in order to provide the BEE2 testbed with a primary user signal with varying transmission power. The BEE2 modular front-end uses a RF reconfigurable modem module at 3.45 GHz and in a spectrum bandwidth of 500 MHz. The RF modem module is provided with two antenna ports: one is used for RF reception, while through the other they perform noise measurements. The test conducted with this architecture enable the CR network performance assessment in terms of probability of missed primary user activity detection and probability of false alarm. Also in [238], different testbed architecture is taken into account to study cooperative spectrum sensing algorithms. Multiple receivers are positioned at different space locations and cooperation algorithms are implemented in the BEE2 structure allowing cooperation among radios to exploit diversity over multi-path, and diversity over shadowing.

8.2.3 **WiNC2R**

The Winlab Network Centric Cognitive Radio (WiNC2R) platform, developed in Rutgers University [240], is a CR prototyping platform that has been designed for flexible processing at both the radio physical layer and MAC/network layers. The main goals of this platform are:

- Multi-band operation, fast spectrum scanning and frequency agility.
- Software-defined modem capable of operating at speeds 10-50 Mbps with OFDM and QPSK/DSSS class waveforms.
- Spectrum policy processing for dynamic spectrum sharing algorithms and etiquette protocols.
- Ability to switch between different MAC algorithms.
- Support for virtualization of multiple PHY/MAC instances.
- High throughput networking operations including ad hoc association and multi-hop routing.

The WiNC2R architecture follows the CR platform architecture scheme introduced above. The WiN2CR software platform uses the GNU Radio code base [241] as its foundation, providing APIs needed for programmability at the PHY and MAC layers. Protocol software used to implement adaptive wireless network capabilities is based on the CogNet software package [242].

8.2.4 WARP: Wireless Open Access Research Platform

WARP is a software defined radio platform originally developed at Rice University [236]. It follows closely the common CR platform architecture discussed above, centred around an FPGA-based motherboard, and supporting up to four radio daughterboards that can be connected to the motherboard. WARP is clearly a relatively high-end SDR platform, supporting up to 4x4 MIMO communications and high physical layer bitrates. The user of the platform has a number of approaches available towards developing software for WARPs, ranging from coding directly for the FPGA, to high-level MATLAB programming. The FPGA has been embedded with a PowerPC processing core in the default configuration, making it possible to use standard "C" in order to develop, for example, medium access control or networking protocols for WARP nodes. The platform has gained a substantial number of users over the past few years, and is currently one of the most widely used platforms for high-end SDR work within the research community. There is also a growing repository of open source implementations of various SDR and cognitive radio functions for WARP, further increasing the appeal of the platform.

8.2.5 KNOWS

The Kognitiv Networking Over White Spaces (KNOWS) project, being developed by a Microsoft and Dell alliance, [243], [244], is a cognitive radio system prototype in which secondary users collaboratively detect white spaces in the TV spectrum, and utilize all the available bandwidth. KNOWS uses a distributed approach to dynamically adjust the operating frequency, the occupancy time, and communication bandwidth, based on the instantaneously available white spaces, the contention intensity, and the user demand. The goal of the KNOWS system is to enable wireless nodes to self-organize into a network without coordination from a central controller to maximize the overall spectrum utilization. The main goals of the KNOWS implementation are:

- Robust white space detection.
- Parallelism and connectivity.
- Adaptive bandwidth selection.

KNOWS uses a collaborative scanning algorithm to detect incumbent operators in the TV bands, a common signalling channel (in the ISM band) to maintain connectivity among nodes, and allows nodes to opportunistically use available spectrum resources by reserving chunks of bandwidth at a fine time-scale.

The main KNOWS components, namely, the hardware, the MAC, and the spectrum allocation scheme of KNOWS are shown in Figure 51 The platform consists of four main function blocks, namely the scanner radio, reconfigurable radio, the GPS receiver, and the x86 embedded processor, explained in the next subsections.

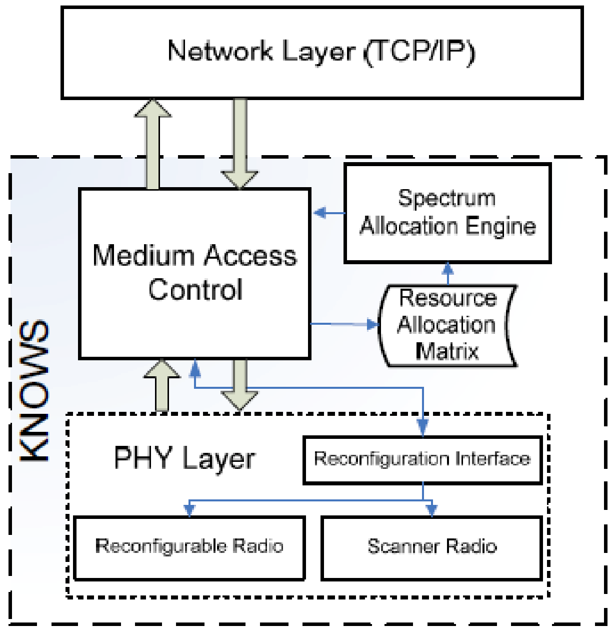


Figure 51: KNOWS main hardware components [244].

8.2.5.1 KNOWS scanner radio

The scanner radio alternates between functioning as a scanner (in the TV spectrum) and a receiver. For most of the time, the scanner radio works as a receiver and is tuned to the 902-928 MHz unlicensed ISM band, which is used as a control channel. To enable efficient spectrum sharing, each node stores the spectrum usage information in a local data structure, the resource allocation matrix (RAM). The spectrum allocation engine uses RAM to determine portions of unused spectrum that the node should reserved for its use. The scanner radio takes advantage from an IEEE 802.11g card to generate OFDM signals at 2.4GHz.

The scanner periodically scans the spectrum and locates the vacant pockets of spectrum without incumbent signals. The scanning algorithm is prototyped in C programming language with a Python-based interface and can be implemented on DSPs or FPGAs. As required by the FCC, the TV spectrum needs to be scanned once every 30 minutes, since the TV signal arrives and leaves in a very coarse time level (several hours).

8.2.5.2 KNOWS reconfigurable radio

The reconfigurable radio has a set of operational parameters that can be adjusted with low time overhead. The current implementation of the reconfigurable radio uses a commodity IEEE 802.11g card to generate the OFDM signals at 2.4GHz. They use a wide band frequency synthesizer to convert the received signals to the specified frequency. To control the reconfigurable radio, the interface to the MAC layer is a list of register values that specifies the operating frequency, bandwidth, and transmission power level. The operating frequency can be set from 400 to 928 MHz in 0.5 MHz steps, and the bandwidth options currently are 5, 10, 20, and 40 MHz.

8.2.5.3 KNOWS GPS receiver

A GPS receiver is incorporated in the hardware board for loading location information and performing time synchronization. Based on the estimated location, the node could identify the unused spectrum in case a database with TV program information was available.

8.2.5.4 *KNOWS x86 embedded processor*

The x86 embedded processor controls all radios on the platform. It takes instructions from the device driver to configure the radios, and passes packets between the host computer and the development board.

8.2.6 **The USRP Platform and GNU Radio-Based CR Testbeds**

Several recently proposed testbeds for CR networks rely on the Universal Software Radio Peripheral, or USRP [245], and the open source GNU Radio software package [241]. In this section, first the USRP product family is introduced, emphasizing the opportunities for practical implementation posed by these devices. Second, an overview of the GNU Radio project is done. The global architecture and the coupling between software and hardware is also illustrated. Finally, several examples of real testbeds for CR networks that have been implemented using this framework are discussed.

8.2.6.1 *The USRP Product Family*

The USRP product family [245], developed and distributed by Ettus Research LLC, is one of the most popular commercial solutions used in the design and implementation of software defined radio systems. The URSP product family consists of the motherboards (the USRP and the USRP2), which contain an FPGA for high speed signal processing, and interchangeable daughterboards, which can cover different frequency ranges, from DC up to a few GHz. Together, they bridge a controller host computer with one or more antennas.

The USRP connects to a host computer by USB 2.0 (480 Mb/s), and can send up to 16 MHz of RF bandwidth in either direction. It contains an FPGA which can be reprogrammed, 4 high-speed Analog to Digital Converters (ADCs), 4 high-speed Digital to Analog Converters (DACs), and a lot of auxiliary analog and digital IO to make integration into a larger system easy. It can accommodate up to 2 transceiver daughterboards, making it 2x2 MIMO capable out of the box.

The USRP2 offers higher performance and increased flexibility than the first motherboard. In this case, the connection to the host computer is done via Gigabit Ethernet, allowing it to send up to 50 MHz of RF bandwidth in and out simultaneously. It contains a larger FPGA which can be used to operate the device in a standalone fashion, without a host computer. It has higher-speed and higher precision ADCs and DACs. The USRP2 holds a single transceiver daughterboard, and multiple USRP2s can be connected together to form very wide MIMO systems (up to 8x8).

Different daughterboards provide the USRP and USRP2 with the appropriate RF front-end for different frequency bands. In addition, a daughterboard can be a single transmitter, a single receiver, or a full transceiver.

8.2.6.2 *GNU Radio*

GNU Radio is an open source project that provides a free software toolkit for developing a software defined radio running on the Linux Operating System on standard PCs [241]. The programming environment is organized around the principle of constructing a signal processing graph that describes the data flow in the software radio. This graph is executed in an integrated runtime system. The vertices of the graph represent signal processing blocks and the edges are the data flow between them. Signal processing blocks are functional entities implemented in C++ which operate on infinite data streams flowing from a number of input ports to a number of output ports specified per block. There are primitive signal processing blocks and hierarchical signal processing blocks, which may aggregate both primitive and hierarchical blocks. GNU Radio provides a large and growing software library of individual signal processing routines as well as complete signal processing blocks, including various modulations (GMSK, PSK, QAM, OFDM), error-correcting codes (Reed-Solomon, Viterbi, Turbo Codes), signal processing constructs (optimized filters, FFTs, equalizers, timing recovery), and scheduling. Signal graphs can be easily constructed using the object-oriented script language Python. This task can be simplified by using the GNU Radio Companion or GRC, which provides a graphical user interface similar to that of Simulink ™.

While GNU Radio is hardware-independent, it directly supports hardware front-ends via specific source and sink signal blocks. Due to its high integration in GNU radio and low cost, the USRP product family is usually coupled with this software framework.

8.2.6.3 Examples of USRP-GNU Radio based testbeds

An initial implementation of a cognitive radio device based on the USRP-GNU Radio platform was shown in [246]. The focus of this paper was on implementing and evaluating the performance of different signal detection, estimation and classification techniques for CR networks. These algorithms were decomposed into logical blocks and implemented in reusable GNU Radio signal processing blocks. These blocks were then demonstrated in an example GNU Radio application, using a USRP board and the DBSRX daughterboard. A second USRP board on an unconnected host computer was used to generate the relevant test signals used for training and detection/classification trials.

A more complete CR transceiver was presented in [247]. In this case, a USRP board using the TVRX daughterboard was used to identify an empty channel in the FM frequency band and consequently transmit an audio stream in it. Once again, a simply energy detector was used to identify an available band and the authors do not mention any further mechanism to change the frequency to another channel if a PU is detected once the transmitter has been established.

Rather than just a transmitter or a receiver, an initial CR network was implemented and demonstrated in [248]. In this case, the network was integrated by two CR users, one acting as the transmitter and the other as the receiver. Each network node was composed of a host computer, a USRP motherboard and the RFX400 daughterboard. The network setup is shown in Figure 52.

The major aim of the paper was to illustrate an initial CR network in which a genetic algorithm was used to select:

- The transmission power: 16 available levels.
- The order of a Phase Shift Keying modulation: 1 to 4.
- The carrier frequency: 428 MHz-459 MHz (32 channels).

in order to:

- Minimize the bit/packet error rate.
- Maximize the throughput.
- Minimize the transmission power.

For some given initial conditions, the transmitter sent a packet to the transmitter, who would then compute usual channel performance parameters such as the Bit Error Rate and net throughput. This information was then sent to the transmitter using a Common Control Channel (CCC), which in this case was emulated using an external TCP connection between the two host computers. Based on this and applying the genetic algorithm, the transmitter would decide whether to change the transmission parameters or not. Two scenarios were considered: optimal power control and transmission rate adaptation in time-varying environment for fixed channel assignment, and dynamic spectrum access in a time-varying jammed spectrum environment. The results showed how the proposed algorithm was able to select the optimal communication parameters in five to six iterations.

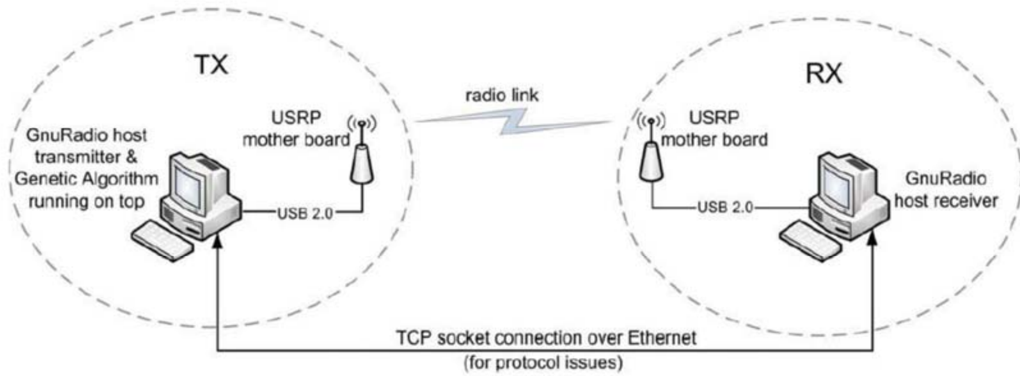


Figure 52: Testing setup of a CR network in [248].

In [249], a complete CR network composed of two CR users and a PU was implemented. Each CR user consisted of a USRP board with two RFX400 daughterboards. A PU was emulated using a Push To Talk (PTT) device. Similarly to previous examples, the CR transmitter performed spectrum sensing using a simple energy detector. Once an empty channel was found, it started to transmit an audio stream. On its turn, the CR receiver would look for the CR transmitter in all possible bands until it found it. By doing this, a Common Control Channel was not necessary.

Up to this point, we have briefly commented several examples of existing testbeds using the USRP and GNU Radio platform. One should note that, so far, these real implementations are limited both in terms of number of users and also complexity of the cognitive stack. In the following two sections, two additional emulation platforms based on this USRP, but which are aimed at using them in a larger scale, are illustrated.

8.2.7 **VT-CORNET**

The Wireless @ VT research group has recently started to develop a new testbed named the Virginia Tech Cognitive Radio Network (VT-CORNET), for the development, testing, and evaluation of cognitive engine techniques and cognitive radio network applications [250]. An open cognitive radio network testbed provides the infrastructure for researchers at Virginia Tech and partner institutions to evaluate independently developed cognitive radio engines, sensing techniques, applications, protocols, performance metrics, and algorithms in a real world wireless environment, in contrast to a computer simulation or single node-to-single node environment.

8.2.7.1 Network Architecture

The VT-CORNET testbed will be composed of 48 radio nodes, spread over 4 floors of a building. Each node will consist of:

- A host computer: initially, convention laptops are using for this purpose, which will progressively be replaced by low-cost and low-energy consumption computing devices based on low voltage CPUs.
- A USRP2 motherboard.
- A custom made daughterboard, spanning the frequencies between 100 MHz and 4 GHz.

Once again, the hardware solution provided by Ettus Research LLC is proved to be one of the most interesting solutions for the development of single software defined radios.

8.2.7.2 Software Platform

Rather than using the open source GNU Radio software, a new software environment based on an implementation of the Software Communications Architecture (SCA) is used [251]. This open-source project, OSSIE, based on an existing software tool developed by the same team of researchers, also models the components of a software defined radio as blocks which are then interconnected in a flow diagram. The SCA specification provides standard interface definitions that make it easy to hook in controllable user interfaces.

The current open source system consists of 6 categories of components (see Figure 53):

- Cognitive Radio Shell (CRS)
- Cognitive Engine (CE)
- Policy Engine (PE)
- Front End (FE)
- Service Management Layer (SML)
- Software-Defined Radio Host Platform

The CRS is the framework core and interacts with the CE and PE over socket connections, while the FE connection is currently accessed through a custom FE library for the specific hardware being used. In particular, they are developing a custom C++ function library to allow the CRS to access the functions of the USRP board, instead of using the extensively used GNU Radio. The socket connections between the CRS and the CE and PE allow the CE and PE to be developed language independent relative to the CRS. Any language that includes a socket library will be able to be used to develop a Cognitive Engine.

One of the main advantages of this platform is that it can be remotely controlled using any network connection. In addition, a web-enabled user interface is being developed to ease even more the task of setting up an experiment.

Note that this network is still being developed and any experiment making use of a real cognitive framework has been reported up to date.

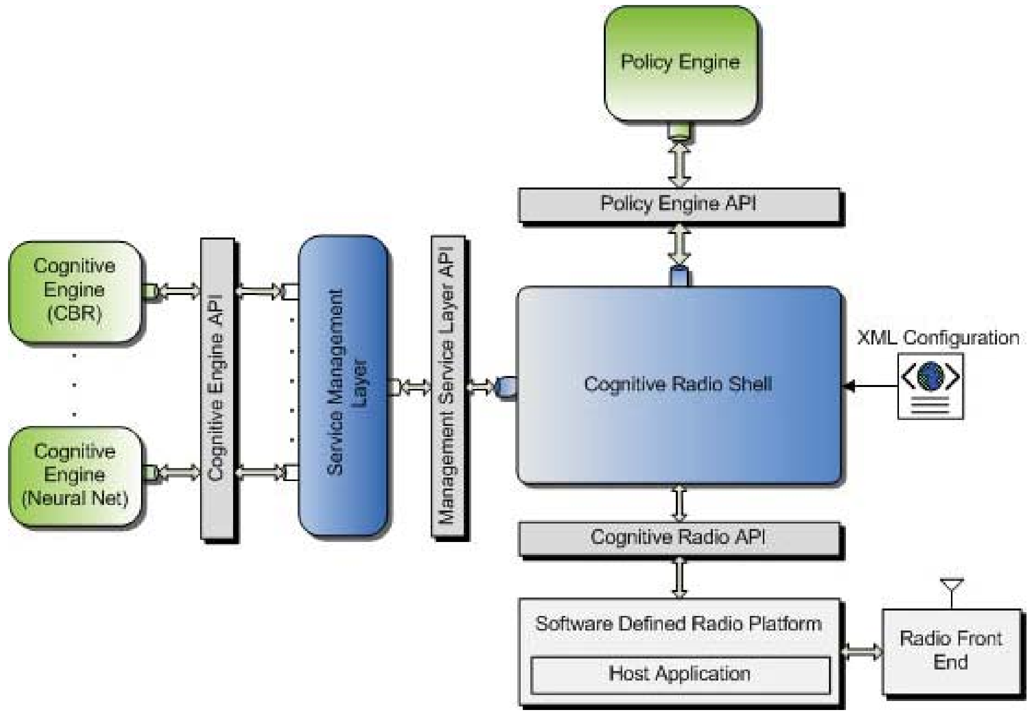


Figure 53: Software framework for the VT-CORNET testbed (from [251]).

8.2.8 EMULAB

Another open access testbed implementation that is worth to be mentioned is the Emulab. The name Emulab refers both to a facility and to a software system. The primary Emulab installation is run by the Flux Group, part of the School of Computing at the University of Utah. There are also installations of the Emulab software at more than two dozen sites around the world, ranging from testbeds with a handful of nodes up to testbeds with hundreds of nodes.

Emulab primarily focuses on networking and distributed systems research. Like WINLAB or CORNET, Emulab is a public facility available to researchers worldwide. The main goal of Emulab is to provide educators and researchers with the ability to perform emulated experiments instead of simulated experiments.

Despite not originally thought as a testbed for future CR networks, several Emulab nodes are currently being equipped with an USRP board and the RFX900 daughterboard. To the best of our knowledge, there are no experimental results reported up to date based on this well-established emulation network. Moreover, note that with these limited daughterboards, the cognitive capabilities of single nodes are certainly limited.

8.2.9 Other Substantial Platforms

There are a lot of different SDR platform available either commercially or as in-house development kits. Many of these are directly usable also for DSA or CR development. Some recent platforms include, e.g. SDR capable equipment from National Instruments (used e.g. by University of Texas), LyrTech manufactured SDRs, CoRAL platform from Communications Research Centre, Canada, SORA development platform from Microsoft Research, etc. Also DARPA has been funding a project aiming at producing a CR platform under the price range of 500 USD. FARAMIR is currently starting to work with the detailed analysis of selected platforms in order to decide which of those are best suited for our testing purposes. As anticipated in the description of work it seems that WARP and USRP2 boards are still quite competitive and state of the art for most of our purposes, with the exception that the detection technology requires more dedicated approaches.

9 Regulations and Standards for Cognitive Radio Networks

9.1 *Regulations*

Reforms in spectrum regulations have been the fundamental driver behind the cognitive radio technology as it is today. This section gives an overview of the recent developments in spectrum regulations on cognitive radio systems in general and some specific to TV white spaces. Although the specifications of spectrum regulations are guided by International Telecommunication Union - Radiocommunication Sector (ITU-R)[252], the allocation of individual spectrum bands are left to the governments and regulatory bodies of their government. It is generally agreed that the current path of spectrum regulation evolution to incorporate more flexible spectrum provisions are advantageous for all stakeholders involved, as long as it takes into account spectrum efficiency and protection against harmful interference.

There is an agenda item for Cognitive Radio Systems (CRS) in ITU-R World Radiocommunication Conference 12 (WRC-12) to be held from 23 January to 17 February 2012 in Geneva, Switzerland and is considered to be a very important step towards realization of cognitive radio technology.

ITU-R WP 5A on "Cognitive Radio Systems" (CRS)

Inside ITU-R (ITU – Radiocommunication Sector), WP 5A [253] has been assigned Question 241-1/5 on “Cognitive Radio Systems”. WP 5A is in preparation of “Working Document towards a Preliminary Draft New Report on Cognitive Radio Systems in the land mobile service”, with the expectation to finalize the ITU-R Report by 2010, addressing the definition, description and application of cognitive radio systems in land mobile service.

ITU-R WP 1B

In addition to WP 5A, ITU-R WP 1B is also working on the Cognitive Radio System topic, since it has been assigned the ITU World Radiocommunication Conference (WRC)-12 Agenda Item 1.19 on "Regulatory measures and their relevance to enable the introduction of software-defined radio and cognitive radio systems". A tight relationship between WP 1B and WP 5A has been established on the CRS topic, including an exchange of liaisons on the definition and on technical details of CRS.

Spectrum Regulation in CEPT member states

Looking at the trends and tendencies towards spectrum regulation in Europe, there are a number of activities regarding more flexible spectrum allocation; in particular the digital dividend and how it can be exploited have gained significant attention. Task Group 4 of the ECC (ECC/TG4) is responsible for preparing the CEPT Reports to the EC Mandates dealing with the digital dividend issue.

On one hand TG4 has to identify the technical requirements (e.g. spectrum masks, channel plans, mitigation techniques) with a view to ensure the protection of radio services, and obligations emerging from relevant international agreements (e.g. on cross border coordination issues) for bands potentially identified for the implementation of the Wireless Access Policy for Electronic Communications Services (WAPECS) concept. On the other hand, it is tasked to continue the work on enhancing harmonisation and increasing flexibility in spectrum management.

Currently, TG4 is working on the following activities:

1. To study the cross border coordination issues between mobile services in one country and broadcasting in another country and to develop relevant guidelines on such issues.
2. To develop a recommendation on the best approach to ensure the continuation of existing Program Making and Special Events services operating in the UHF (470- 862 MHz), including the assessment of the advantage of an EU-level approach.
3. To encourage exchange of best practices on rearrangement activities for broadcasting in order to free the sub-band and develop relevant guidelines (reports or recommendations) on such issues.
4. To carry out additional measurements on protection ratios for the protection of broadcasting in order to assist administrations in determining the precise situation in terms of compatibility.

Among the current activities, it is the second one that is of interest as far as the SDR and CR technologies are concerned.

Regulations in TV White Space (TVWS)

In the US, Federal Communications Commission (FCC) issued a docket on the use of cognitive radio (CR) in TV white spaces in 2008 [254]. The FCC pursued a range of activities, including a number of consultations and requests for opinion, etc. with regard to a more efficient use of spectrum. On November 4th 2008, the FCC adopted a Second Report and Order (Second R&O) **[255]**. This document establishes the rules that will allow new, more capable wireless devices to operate, as secondary user, in the broadcast television spectrum. There is however a restriction as in secondary access is only allowed in situations where the spectrum is not used by the primary user (i.e. only in the television WS – television White Spaces).

Analysing the rules, they have been very carefully formulated and do allow the operation of unlicensed devices (in the television WS), as long as incumbent services and users are protected against harmful interference. The FCC report foresees a mix of technologies to enable unlicensed equipment to ensure that harmful interference can be avoided; this includes the establishment of databases where equipment and its operational parameters/range can be temporally (as long as applicable) registered as well as rather severe requirements towards the white space identification capability (i.e. sensing capabilities of equipment). This means that the FCC will permit certification of devices that do not include location or database access capabilities, although these devices, relying entirely on their spectrum sensing capabilities to meet the interference avoidance criteria, will be subject to a rigorous approval process. While the rules do allow a large degree of flexibility, the FCC will monitor the actual situation and will enforce the protection against harmful interference through removing failing equipment from the market.

On 25th November 2009 FCC issued a call for proposal called ET Docket 04-186 **[256]**, inviting to be administrators of TV white space database. By January 2010 (deadline), 9 companies have proposed to be the white space database manager. It is interesting to note that multiple administrators working together in the same geo-location were also discussed.

In the UK, Ofcom has proposed rules of how CR could be operated in the TV broadcast bands, factually paving the allowing secondary usage [257]. However, comparing the requirements issued by Ofcom with those issued by the FCC, the type of receivers that could be deployed as secondary users would require a very high sensitivity and very low reaction time.

In Europe, the CEPT has created a technical Project Team (WGSE/PT43) to define technical and operational requirements for the operation of cognitive radio systems in the white spaces of the UHF broadcasting band (470-790 MHz) to ensure the protection of incumbent radio services/systems and investigate the consequential amount of spectrum potentially available as "white space". It shall be noticed that the technical and operational use of the broadcasting band in Europe is radically different from the US one. An overview of European regulatory technical conditions in the specified TV bands is presented in [258].

9.2 *Standards*

The rapid evolution in the field of next generation radio and advanced spectrum management has prompted the need for coordinated work on Cognitive Radio standardization. The prominent standardization bodies in the telecommunications sector have begun tackling different aspects of CR, as well as its compatible counterparts software defined radio (SDR) and dynamic spectrum access (DSA). IEEE is leading the standardization process through the IEEE 802.22 standard and the IEEE SCC41/P1900 series of standards. Enhancements on existing IEEE 802 standards towards cognitive radio are also being developed [175]. ITU has been engaged into a more global approach within the ITU – R working party 5A [253]. Since March 2008, ETSI has established a technical committee in the area of reconfigurable radio systems (RRS) [258]. Other standardization bodies working in related areas are IEEE 802.11af, IEEE 802.19 and IEEE 802.21. The Wireless Innovation Forum (formerly, SDR Forum) is business forum that is relevant to this project.

In this section, the activities carried out in several standardization bodies for CR networks are briefly described, pointing out the still open challenges in terms of standardization.

9.2.1 **IEEE 802.22 WRAN**

Spectrum usage measurements of TV bands have shown low level of spectrum utilization. Propagation characteristics in the region of 41MHz – 910MHz band (54MHz – 862MHz in North America) are more suitable for long range communications due to the lack of industrial noise and ionospheric reflections. IEEE 802.22, [259], is a standard for Wireless Regional Area Network (WRAN) that works in the TV band region, providing cell coverage range of up to 100km (designed for 17-30km) and capability for serving 255 customer premises equipments (CPEs). The development of the IEEE 802.22 WRAN standard is aimed at using cognitive radio techniques to allow sharing of geographically unused spectrum allocated to the Television Broadcast Service, to bring broadband access to hard-to-reach, low population density areas, typical of rural environments, and is therefore timely and has the potential for a wide applicability worldwide, as shown in Figure 54.

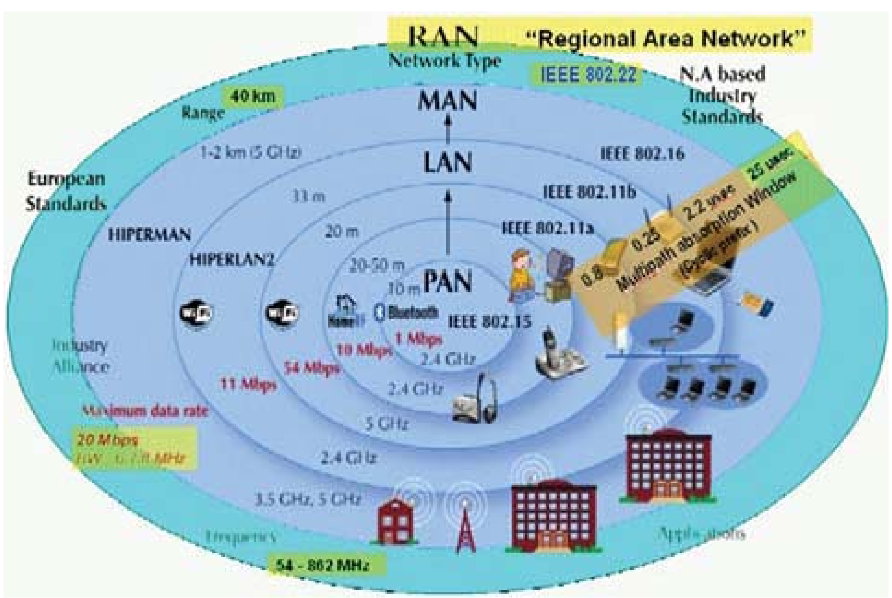


Figure 54: Positioning of WRAN amongst IEEE 802 wireless networks [259].

The IEEE 802.22 working group on Wireless Regional Area Networks was formed in October 2004. Its project, formally called *Standard for Wireless Regional Area Networks (WRAN) - Specific requirements - Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and procedures for operation in the TV Bands* focuses on constructing a consistent, national fixed point-to-multipoint WRAN that will use UHF/VHF TV bands between 54 and 862 MHz. Specific TV channels as well as the guard bands of these channels are planned to be used for communication in IEEE 802.22.

The key new concepts introduced in the IEEE 802.22 standard are the cognitive aspects. Control of channel usage and CPEs' maximum effective isotropic radiated power (EIRP) are the main cognitive functions required for proper operation of 802.22 systems (non – interference with incumbent users). Enabling these functions is done through utilization of three cognitive tools: effective geo - localization, channel availability database and spectrum sensing. In that sense, a centralized approach for available spectrum discovery is proposed in this standard. Specifically each Base Station (BS) in the network would be provided with a GPS receiver which would allow its position to be reported. This information would be sent back to centralized servers, which would respond with the information about available free TV channels and guard bands in the area of the BS. Other proposals would allow local spectrum sensing only, where the BS would decide by itself which channels are available for communication. A combination of these two approaches is also envisioned. Devices which would operate within this standard are of two types: fixed device and Personal/Portable device. The Fixed devices would have geo location capability with embedded GPS device. Fixed devices also communicate with central database to identify other transmitters in the area operating in the aforementioned band.

On the other hand, additional measures suggested by the FCC and IEEE to avoid interference, rely on dynamic spectrum sensing and dynamic power control. In this context, spectrum sensing is done on the operating and adjacent channels for insurance that no incumbent is present. If possible interference is detected on an incumbent the spectrum manager will choose one of four options: reducing the EIRP of the CPE, disallowance of CPEs if the limited EIRP is too low for service sustainability, reducing the EIRP of the BS and channel movement for both the BS and the associated CPEs if the BS EIRP is too low.

On the other hand, different WRAN systems should be able to effectively operate, when deployed in each others' vicinity. Coexistence is enabled through a self - coexistence mechanism based on the Coexistence Beacon Protocol (CBP) protocol and appropriate spectrum sharing schemes. The CBP protocol uses beacon transmissions between adjacent WRAN cells, which convey all necessary information needed for network discovery, spectrum sharing and coordination.

With more than five years down the road, the current efforts are focused on these three main issues:

- **IEEE P802.22:** the main standard specification and policy, currently being addressed by IEEE 802.22 working group (WG).
- **IEEE P802.22.1:** a standard being developed to enhance harmful interference protection for low power licensed devices operating in TV Broadcast Bands currently being studied by the IEEE 802.22 Task Group 1 (TG1).
- **IEEE P802.22.2:** a recommended practice for the installation and deployment of IEEE 802.22. Systems, developed by the IEEE 802.22 Task Group 2 (TG2).
- **IEEE 802.22.3**: A PAR is approved to support **scalable operations** of WRAN rendered feasible by the new regulatory environment that allowed both fixed and personal/portable unlicensed devices to operate on unused television channels.

9.2.2 IEEE P1900- Standards Coordinating Committee 41 (SCC 41)

The IEEE P1900 Standards Committee [260] was established in the first quarter of 2005 jointly by the IEEE Communications Society (ComSoc) and the IEEE Electromagnetic Compatibility (EMC) Society. The objective of this effort was to develop supporting standards dealing with new technologies and techniques being developed for next generation radio and advanced spectrum management. In 2007, the IEEE Standards Board approved the reorganization of the IEEE 1900 effort as Standards Coordinating Committee 41 (SCC 41), Dynamic Spectrum Access Networks (DySPAN) whose scope was to sponsor standards projects in the area of dynamic spectrum access networks and provide coordination and information exchange between and among standards developing activities of the IEEE.

The IEEE SCC 41 is divided in the following groups, [261]:

- *IEEE 1900.1 - Working Group on Terminology and Concepts for Next Generation Radio Systems and Spectrum Management:* provide technically precise definitions and explanations of key concepts in the fields of spectrum management, cognitive radio and related technologies from different perspectives. The standard also describe how these technologies can be used in a wide variety of communication service environments to achieve new capabilities while at the same time providing mechanisms supportive of new spectrum management paradigms and spectrum access. The standard is now published.

- *IEEE 1900.2 - Working Group on Recommended Practice for Interference and Coexistence Analysis:* provides a model that facilitates the analysis of coexistence/interference between CR users and PUs operating in the same frequency band or between different frequency bands. The model also provides guidance for estimating the co-channel, adjacent channel and out of-band interference under a variety of scenarios. It also analyses how factors such as directional antennas, power control, and licensed channel avoidance strategies affect the aggregate interference. In summary, the standard provides a framework for measuring and analyzing the coexistence of different systems including the uncertainty levels in measurement and thresholds of harmful interference. The standard is now published.

- *IEEE 1900.3 - Working Group on Recommended Practice for Conformance Evaluation of Software Defined Radio (SDR) Software Modules:* The WG has been disbanded.

- *IEEE 1900.4 - Working Group on Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks:* aimed to increase the overall system utilization of reconfigurable terminals while increasing the perceived QoS. It does this by defining the overall system architecture in such a way so as to split functionality between terminals and the network and also the information exchange between coordinating entities for optimized resource management in a heterogeneous wireless access network. Within this resource management system built on top of a heterogeneous wireless network, two key entities are defined, i.e. a Network Reconfiguration Manager (NRM) and a Terminal Reconfiguration Manager (TRM). The interfaces between these management entities are also specified, the most important of which is the Radio Enabler interface (RE) between the NRM and the TRM.
  Distributed radio resource usage optimization covers the optimization procedures for radio resource usage, which is performed by both the heterogeneous wireless network and the terminals in a distributed fashion. This two stage procedure begins with the NRM reaching an optimum on a global objective. The global optimum is then conveyed to the TRM through

the RE interface. Subsequently each TRM reaches an optimum on a local objective, derived from the user needs (e.g. throughput, QoS requirements, user preferences etc.), while maintaining compliance with the constraints specified by the NRM.

Realizing this distributed resource management assumes reconfiguration and cognitive capabilities of base stations and terminals. The system requirements can be classified in three categories, one for each reconfiguration/cognition phase: obtaining context awareness information, making reconfiguration decisions, and the execution of the actual reconfiguration.

- Context awareness is achieved by collecting context information both at the RAN and terminal level. The RAN context information is collected at the NRM and is used for creating a constraint policy for the TRMs, while the terminal context information is collected at the TRMs and is used as an input for the terminal reconfiguration decision.
- Decision making is the second step. Optimal decisions are first reached at the network side and then sent to the TRM as policies. Two types of policies are defined in 1900.4: spectrum assignment and radio resource selection policies. The TRM manages the terminals (reaches optimal decisions) in accordance with the framework defined by the policies and the terminal side requirements.
- Reconfiguration execution is the final system requirement in IEEE 1900.4. The reconfiguration entity on the network side carries out the actual reconfiguration procedures as specified by the NRM, and the reconfiguration entity at the terminal side executes the terminal reconfigurations based on TRM requests.

The system architecture defined in the IEEE 1900.4 standard is shown on Figure 55, where we can distinguish 7 separate entities and 6 interfaces. The network side is comprised of:

- Operator spectrum manager (OSM) - enables the operator to control the NRM's dynamic spectrum assignment
- RAN measurement collector (RMC) – collects RAN context information and provides it to the NRM
- NRM is the key function in the network side and performs six functions i.e. policy derivation, policy efficiency evaluation, network reconfiguration decision and control, spectrum assignment evaluation, information extraction, collection, and storage, and RAN selection.
- RAN reconfiguration controller (RRC) – controls the reconfiguration at the network side

At the user side three entities are defined:

- Terminal measurement controller (TMC) – collects terminal context information and provides it to the TRM
- TRM is the key function in the terminal side and performs three functions e.g. terminal reconfiguration decision and control function (responsible for the terminal reconfiguration decisions); terminal side information extraction, collection and storage; terminal side RAN selection.
- Terminal reconfiguration controller (TRC) – controls the reconfiguration at the user side.

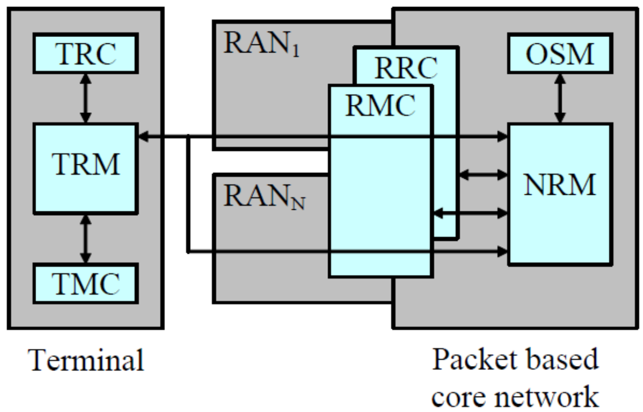


Figure 55: IEEE 1900.4 system architecture [262].

The general functional architecture with all of the aforementioned functions and their relationship as specified in the IEEE 1900.4 standard is shown on Figure 56.

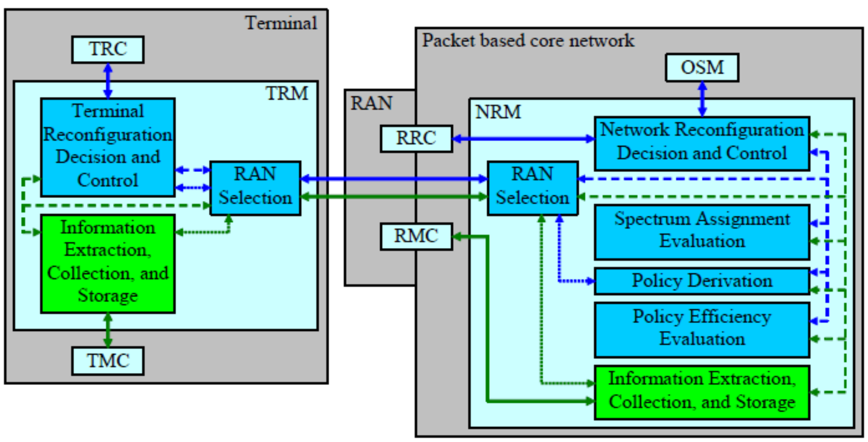


Figure 56: IEEE 1900.4 functional architecture [262].

Finally, notice that the IEEE 1900.4 working group is the central WG of the P1900 series. The standard is now published.

1900.4a PAR - The IEEE P1900.4a is the amendment that defines the architecture and interfaces for dynamic spectrum access networks in white space frequency bands. P1900.4a uses IEEE standard 1900.4 as a baseline. P1900.4a defines additional entities and interfaces to enable the efficient operation of white space wireless system. This WG is currently active and finalizing draft standard.

1900.4.1 PAR – The IEEE P1900.4.1 is the standard for interfaces and protocols enabling distributed decision making for optimized radio resource usage in heterogeneous wireless networks. This WG is currently active and finalizing draft standard.

- *IEEE 1900.5 - Working Group on Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access Applications:* defines a set of policy languages, and their relation to policy architectures, for managing the features of cognitive radios for dynamic spectrum access applications. Policing is one of the key concepts in the cognitive radio realm.

Then, initially the focus will be on standardizing the basic features of a policy language so that it can be bound to one or more specified policy architectures. Additional tasks will be built on top of this foundation, while maintaining attention to interoperability and vendor–independency. This WG is currently active and finalizing draft standard.

- *IEEE 1900.6 - Working Group on Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and other Advanced Radio Communication Systems:* aimed to develop a standard that will define the interfaces and data structures required for exchange of sensing related information. The resulting standard will provide a formal definition of data structures and interfaces for exchange of sensing related information. The interfaces and data structures are defined abstractly without putting constraints on the spectrum sensing technology on the one side, the system design on the other and the data link in between. Consequently, the IEEE 1900.6 standard lays out the guidelines for achieving interoperable modularity. This WG finalizing draft standard and would go for sponsor balloting soon.

Finally, it should be noted that the IEEE P1900 series cooperate between each other and with other IEEE based working groups such as IEEE 802.18, IEEE 802.19, IEEE 802.21 and IEEE 802.22.

Despite the efforts on standardization of future CR networks are apparently increasing, this more ambitious standard is still far from being mature. In addition, only by close interaction between research centres, universities and the major companies in the telecom business, a standard satisfying all the parts involved will be obtained.

9.2.3 ETSI RRS – Overview and Role in the European Regulatory Framework

The ETSI Reconfigurable Radio Systems (RRS) Technical Committee (TC) was created in January 2008, with the mandate of taking the responsibility for promoting the standardization activities related to Reconfigurable Radio Systems encompassing system solutions related to Software Defined Radio (SDR) and Cognitive Radio (CR). To this end the ETSI RRS TC collects and defines the related Reconfigurable Radio Systems requirements from relevant stakeholders; and it also identifies gaps, where existing ETSI standards do not fulfil the requirements, and suggests further standardization activities to fill those gaps.

Therefore, the ETSI RRS TC is addressing some issues that are complementary to the IEEE SCC41 and IEEE 802 activities, with a focus on:

i) SDR standards beyond the IEEE scope,

ii) CR/SDR standards addressing the specific needs of the European Regulatory Framework. In that sense, the Electronic Communications Committee (ECC) within the European Conference of Postal and Telecommunications Administrations (CEPT) has set up the SE43 group working on "Technical and operational requirements for the operation of cognitive radio systems in the 'white spaces' of the frequency band 470-790 MHz". ETSI RRS body is the competence centre within ETSI to implement those regulatory requirements.

iii) CR/SDR TV White Space standards adapted to the digital TV signal characteristics in Europe. Certainly, in Europe, DVB-T does not show a residual carrier as it is the case in the US[2] . Therefore, specific sensing based standards needs to be defined for Europe.

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2 The possibility for detection of the US ATSC signal below noise (i.e., at -114 dBm) is made possible thanks to the residual carrier which is present in the ATSC signal.

The ETSI RRS Technical Committee is structured in the following four Working Groups (WGs):

1) WG1 focuses on "System Aspects" and develops proposals from a system aspects point of view for a common framework in TC RRS with the aims to guarantee coherence among the different TC RRS WGs and to avoid overlapping and gaps between related activities. WG1 has conducted feasibility studies on Cognitive Radio Systems (CRS) concept and potential regulatory aspects of CRS and SDR, [263]. Two new work items (WI) have been recently approved, namely "Operation in White Space Frequency Bands" and "Cognitive Radio Network Coexistence on White Spaces".

2) WG2 focuses on SDR technology with a particular interest in "Radio Equipment Architecture" and proposes common reference architectures for SDR/CR radio equipments (mobile handset devices, radio base stations, etc.), related interfaces, etc. The base stations related work is currently in an early stage and available results are resumed in [264], whereas the current focus in mobile devices mainly on SDR related interface standardization between distinct stakeholder domains, such as SDR chipset vendors and mobile devices manufacturers, [265]. In the context of this SDR mobile devices framework, a reference architecture has been derived which outlines the relevant interfaces and concerned building blocks. However, this envisaged architecture is not meant to be normative.

3) WG3 focuses on "Cognitive Management and Control"; the group collects and defines the system functionalities for Reconfigurable Radio Systems which are related to the Spectrum Management and Joint Radio Resource Management across heterogeneous access technologies. Furthermore, the group has developed a Functional Architecture for the Management and Control for Reconfigurable Radio Systems, [266], as well as a report on the Cognitive Pilot Channel as an enabler to support the management of the RRS, [267].

4) WG4 focuses on "Public Safety" and collects and defines the related RRS requirements from relevant stakeholders in the Public Safety and Defense domain. The group defines the system aspects for the applications of RRS in Public Safety and Defense, [268].

The overall cognitive radio system concept developed by ETSI RRS is depicted in Figure 57. The figure covers both centralized and decentralized solutions for CR systems, where the centralized, operator-driven solution is targeted for wide area utilization, and the decentralized solution is targeted for local area ad-hoc/mesh networking. The centralized CRS concept is represented by the Composite Wireless Network (CWN) including Cognitive Network Management System (C-NMS). C-NMS contains such key components as Operator Spectrum Manager (OSM) and Joint Radio Resource Management (JRRM). The decentralized CRS concept is represented by the Cognitive Mesh Network (CMN) controlled by the Cognitive Control Network (CCN).

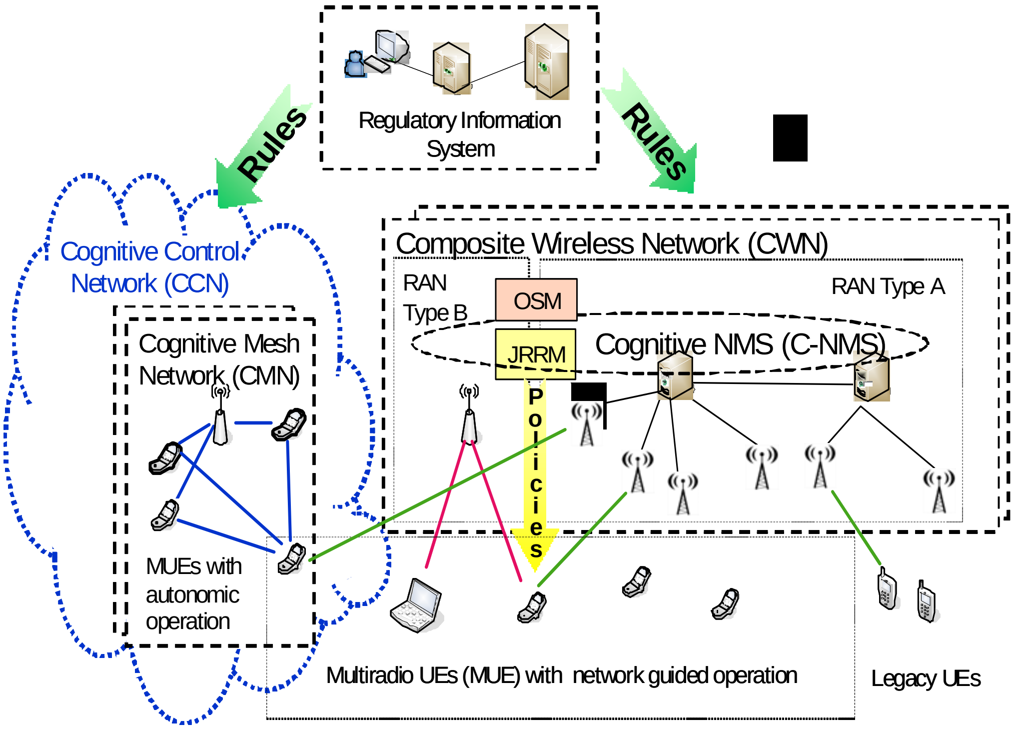


Figure 57: Centralized and Decentralized CR System Concepts (from [263]-[268]).

The ETSI RRS TC has also identified key enabling technologies for CRS. They include software defined radio and multiradio, reconfigurable base stations management, spectrum sensing, cognitive pilot channel, cognitive control radio and networking, geolocation, primary protection database, and distributed decision making.

From December 2009 on, the group is mandated to produce normative standards in the field of CR and SDR, instead of study reports.

9.2.4 Other Relevant Standard Activities

IEEE 802.11af: The IEEE 802.11 Task Group af (TGaf) is the amendments to both IEEE 802.11 Physical layer (PHY) and Medium Access Control (MAC) layer to meet the legal requirements for channel access and coexistence in the TV white space.

IEEE 802.19: Many of the IEEE 802 wireless networks use unlicensed spectrum and hence the issue of *coexistence* of different wireless networks within the the same location needs to be addressed. IEEE 802.19 is the Wireless Coexistence Technical Advisory Group (TAG) within the IEEE 802 LAN/MAN Standards Committee dealing with such coexistence issue.

Following the recent developments in TV White Spaces, a new working group TG1 was approved. The purpose of IEEE 802.19 Task Group 1 is to enable the family of IEEE 802 standards to most effectively use TV white space by providing standard coexistence method among dissimilar or independently operated TV Band Device (TVBD) networks and dissimilar TVBD devices.

ECMA-392: ECMA International is an industry association founded in 1961 and dedicated to the standardization of Information and Communication Technology (ICT) and Consumer Electronics (CE). In Dec. 2009, ECMA published a Standard called ECMA-392 entitled “MAC and PHY for Operation in TV White Space”. This Standard specifies a MAC layer and a PHY layer for cognitive wireless networks operating in TV bands. This standard also specifies a MUX (a session management protocol) sub-layer for higher layer protocols. It also specifies a number of incumbent protection mechanisms which may be used to meet regulatory requirements.

10 Conclusions

There have been significant advancements towards realizations of cognitive radios, as well as towards the development of the various enabling technologies needed for the diverse potential application scenarios of CRs. Nevertheless, we have also seen that a lot of further research and development work is definitely needed before general cognitive wireless networks can be realized. Technologies required for realising the dynamic spectrum access scenario are somewhat more developed than those needed for scenarios such as coexistence of heterogeneous wireless networks, or applications in vehicular and ad hoc networks. However, even in the DSA case problems remain, especially in how to deal with uncertainties in the propagation environment, and in the development of more advanced sensing technologies.

We have seen that environmental information is key to enabling applications of cognitive radios in practically all the scenarios considered. Radio Environment Maps provide means for dealing with diverse types of environmental information, and thus are at the heart of practical cognitive wireless network architectures. However, despite their importance, there has been very little work in the research community or within industry towards enabling general REMs that would go beyond the simple geolocation database approach. Thus the core objective of the project is still extremely relevant, and potential impact high. The challenges that have to be addressed in the REM design work include development of a general enough and extendible data model, design of an architectural framework that allows flexibility both at deployment and runtime, specification of the various interfaces used to interact with REMs, and selection or development of the different algorithms dealing with the information stored in them. All of these issues will be addressed within FARAMIR.

Work is also needed in different enabling technologies. Classical spectrum sensing approaches, such as energy or feature detection, are reasonably well understood both in terms of theoretical performance as well as practical implementation complexity, although as we have seen some challenges especially in the implementation area still remains. However, there are significant opportunities in extending these approaches towards more complete radio neighbourhood characterisation. For example, using advanced signal processing techniques to estimate directionality of interference or further properties of the transmitters emitting those signals has potential to significantly improve the quality of decisions made based on spectrum sensing data. Also, existing algorithms for processing and reasoning about outputs of spectrum sensors often assume significant amount of knowledge on, for example, the propagation environment. Obtaining such information in practise is not straightforward, and there is definitely need to develop methods for forming and updating propagation models in online fashion. This involves solving both deep statistical problems, as well as practical wireless communications challenges.

Some of the additional observations and conclusions that we have arrived while carrying out the review work are:

- Although patenting has become more active in the field, the number of patents is still relatively low (see Annex III), especially if one consider which patents could be estimated to be essential ones.
- Literature and state of the art in the sensing techniques is very advanced, but there are still lack of public literature and work in the area of directional sensing techniques and specific DSP algorithms for efficient implementation of such techniques.
- Standardization activities have been getting more prominent, but they are still in the relatively early phases and some standard texts exhibit quite high abstraction level.
- REM based literature is still limited, and mostly offer high level proposals without quantitative details or detailed analysis.
- Although the first prototyping environments have started to emerge, there is still a general lack of integrated demonstrators and prototypes which would include all the key components of cognitive radios.

- Even though the number of spectrum occupancy measurement campaigns could be could be described as adequate, it is far from perfect. The comparison between different existing measurement campaigns is often difficult and cumbersome, sometimes even impossible. The review indicates a strong need to have larger measurement campaigns with wide coverage area and the need to use common methodology. Moreover, there is also need to correlate some of the measurements with the know ground truth of spectrum use, e.g. in cellular bands. Furthermore, we have found out that in some areas which we could even call fundamentals there is still lack of understanding and measurements, for example general empirical characterization of shadow correlations.
- In the spectrum policy domain with regards to DSA some of the regulators have taken proactive steps towards allowing at least limited operations. Most notable is the recent decision by FCC to enable use of TV white spaces in opportunistic fashion. Also OFCOM has been active in this domain, including their own measurement campaigns that have been conducted to understand opportunities and limitations of DSA based technologies. There has been also recent moves to allow at least research based testing, such as a recent decision by Finnish spectrum regulator (FICORA) to allow cognitive radio research in the frequency range of 470-790 MHz (this ruling allows also operations without need to use regional spectrum database).

Finally, in addition to work on REMs and filling in missing pieces in enabling technologies, notable conclusion from the review is that there still are very few actual CR testbeds or deployments, especially going beyond the basic IEEE 802.22 DSA applications. FARAMIR will specifically address this issue by developing prototype implementations of all the major components, and by integrating them into concrete cognitive wireless network prototypes. Those prototypes will then be tested, evaluated and demonstrated in scenarios specifically designed to illustrate the power and potential of general cognitive radio concepts and applications going well beyond “simple” dynamic spectrum access. This more systems-oriented approach will also necessitate work in practical resource management and control plane solutions for cognitive wireless networks, which we expect to be of independent interest to the research community and wireless communications industry alike.

Annex I: Terminology

Ad Hoc Network: An ad hoc network is an autonomous collection of routers/stations that have the ability to dynamically and rapidly form networks without the use of any centralized network infrastructure or manual intervention. Ad hoc networks distinguish themselves by using adaptive self-configuring protocols to enable the network itself to meet the changing demands of its users in an ad hoc manner within the constraints imposed on it by dynamic network conditions.

Adaptive Radio: Radio in which communications systems have a means of monitoring their own performance and a means of varying their own parameters by closed-loop action.

Advanced Collaborative Sensing: Individual cognitive radio devices could combine cognition capabilities and information to achieve a set of goals that benefit all participants or reach a global consensus regarding a particular scenario. One example of this application is a distributed sensor mesh network used to build a map of the wireless activity in a wide area for frequency planning and allocation, device detection and movement pattern monitoring.

Cognitive Network (CN): Cognitive network generally addresses the future networks being able to sense the radio environment, interpreting the radio environment, reacting to the changes, tuning the radio and implementation parameters and self-healing.

Cognitive Pilot Channel (CPC): A logical or physical channel connecting cognitive radios and cognitive networks with the aim of conveying necessary information to supply cognitive terminals with information on available frequency bands, Radio Access Technologies, services, load situation, network policies, etc at different geographical locations.

Cognitive Pilot Channel (CPC) (ETSI-RRS definition): channel which conveys the elements of necessary information facilitating the operations of Cognitive Radio Systems

Cognitive Radio (CR):
A type of Radio in which communication systems are aware of their environment and internal state and can make decisions about their radio operating behaviour based on that information and predefined objectives, and learn from the outcomes of the decisions it has made, implementing the complete cognitive cycle given in Figure 5. Cognitive Radios are often implemented on Reconfigurable Radios, but this is not strictly speaking required, provided that higher layers have reconfigurability the cognitive cycle can interact with.

Note - The environmental information may or may not include location information related to communication systems.

Cognitive Radio System (ITU-R WP 1B definition): a radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained.

Cognitive Interference Avoidance (P1900 definition) **:** The process by which a cognitive radio system identifies spectrum dependent devices with which it may potentially cause or receive interference and adapts its operating parameters to avoid such interference.

Note - There are several techniques for cognitive interference avoidance. For example, a cognitive radio may provide a new orthogonal modulation waveform with respect to the interferer or search for available spectrum.

Cooperative Sensing: In cognitive radio systems, two or more wireless nodes combining their capabilities and spectrum-usage resources using negotiated or prior arrangements, is a common way for cognitive radios to have a more global sense of spectrum usage.

Collaborative Use of Spectrum (P1900.1 definition**):** The process of two or more radio nodes combining their capabilities and spectrum-usage resources via negotiated or pre-determined policies and agreements to improve the expected utility of the network.

Cross-layer (P1900.1 definition): Technique for monitoring the protocol stack and adapting the protocol composition when needed to bypass typical ISO stack interactions and provide a specific capability.

The cross layer approach transports feedback dynamically via the layer boundaries to share information between different communications layers in order to increase the knowledge and current state of the network. This could enable new and more efficient protocols to be developed.

Dynamic Channel Allocation (DCA): Radio resource for a particular service is not managed in a dedicated manner. The optimal channel allocation is realized by measuring service profile in terms of the temporal communication quality.

Dynamic Channel Assignment (DCA) (P1900.1 definition)**:**

The process of selecting and assigning different channels in real time to various entities/devices by making use of the available data regarding the operating environment to enhance performance.

The transient radio frequency channel assignments created by radios, radio networks, or other spectrum dependent systems that engage in Dynamic Spectrum Access. This contrasts with the static channel assignments that result from the traditional static Spectrum Management process, where radio devices operate in one predefined frequency range.

Note - DCA may be performed by external parties, that do not take part in the communication process (see spectrum broker) or by the system/network itself where system/network has one or more logical entity responsible for transient radio frequency channel assignment.

Dynamic Spectrum Access (DSA) (P1900.1 definition)**:** The real-time adjustment of Spectrum Utilization in response to changing circumstances and objectives.

Note - Changing circumstances and objectives include (and are not limited to) energy-conservation, changes of the radio's state (operational mode, battery life, location, etc.), interference-avoidance (either suffered or inflicted), changes in environmental/external constraints (spectrum, propagation, operational policies, etc.), spectrum-usage efficiency

Dynamic Spectrum Allocation (DSA): DSA refers to the partitioning of the spectrum that dynamically changes to adapt to the current or future demand on the radio resources resulting in certain gain in spectrum allocation. The gain in DSA could lead to an increase in the system capacity or could translate to the reduction on the system cost capabilities and estimation of the duration of spectrum occupancy.

Dynamic Spectrum Assignment (DSA): A cell-by-cell spectrum assignment that is changed during the cellular network operation to adapt to variable network conditions.

Dynamic Spectrum Assignment (DSA) (P1900.1 definition) :

The continuous update of assignment of specific frequencies or frequency bands within a wireless network operating in a given region and time to optimize spectrum usage.

The dynamic assignment of frequency bands to Radio Access Networks within a Composite Wireless Network operating in a given region and time to optimize spectrum usage.

Note - The definition in b) is specific to a class of network and device dynamic reconfiguration scenarios that enable coordinated network-device distributed decision making, including spectrum access control in heterogeneous wireless access networks as described in the draft standard for Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks being developed by SCC41 project P1900.4

Dynamic Spectrum Management (DSM) (P1900 definition**):** A system of spectrum management that dynamically adapts the use of spectrum in response to information about the use of that spectrum by its own nodes and other spectrum dependent systems.

Note - Dynamic Spectrum Management helps to address the inherent inflexibility of static band allocations and the ability of future networks to simultaneously carry traffic corresponding to multiple radiocommunications services.

Femtocell: A low-range, user-deployed access point to mainly provide indoor coverage at homes or offices.

Hierarchical Spectrum Access (P1900 definition**):** A type of spectrum access in which a hierarchy of radio users or radio applications determines which radios have precedence.

Note - The most common hierarchy proposed today is one that distinguishes between primary users and secondary users. In this hierarchy, secondary users may only access spectrum when primary users are not occupying it. However, other hierarchies are possible, including the existence of tertiary users or hierarchies based on the type or criticality of the communication. The hierarchy may be determined by a central authority, such as regulator, or through active collaboration among affected systems. The hierarchy may be static or it may be established dynamically based on the current environment

Interference (P1900 definition**)**
In a communication system, interference is the extraneous power entering or induced in a channel from natural or man-made sources that might interfere with reception of desired signals or the disturbance caused by the undesired power.

Radio-Frequency Interference: The effect of unwanted energy due to one or a combination of emissions, radiations, or inductions upon reception in a radiocommunication system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy.

Harmful Interference: Interference which endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with these Regulations.

Note - The term "Regulations" in the definition of Harmful Interference refers to the ITU Radio Regulations.

Interference (ITU-R definition): The effect of unwanted energy due to one or a combination of emissions, radiations, or inductions upon reception in a radiocommunication system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy.

Link Adaptation: The task of dynamically assigning modulation and channel coding schemes to scheduled users' transmissions by packet scheduler.

Medium Access Control (MAC): The data link sublayer that is responsible for transferring data to and from the Physical Layer.

Note - A MAC protocol generally consists of a collection of components, each performing a special function, such as the support of higher layer traffic, the synchronization process, the bandwidth allocation, and the contention resolution mechanism.

Mesh network: Mesh network is a type of network wherein each node in the network may act as an independent router, regardless of whether it is connected to another network or not. It allows for continuous connections and reconfiguration around broken or blocked paths by "hopping" from node to node until the destination is reached. Mesh networks are often assumed to be at least partially static, in contrast to ad hoc networks.

Opportunistic Spectrum Access: Dynamic spectrum access by secondary spectrum users that exploits local and instantaneous spectrum availability in a non-interfering manner and without primary user negotiation.

Opportunistic Spectrum Management: A type of Dynamic Spectrum Management used to manage Opportunistic Spectrum Access.

Quality of Service (QoS) (P1900.1 definition)
A defined level of service quality provided by a network. In general, it may be defined by throughput, availability, latency, jitter, and error rate.

The collective effect of service performance which determines the degree of satisfaction of a user of the service.

Note 1 - The quality of service is characterized by the combined aspects of service support performance, service operability performance, serveability performance, service security performance and other factors specific to each service.

Note 2 - The term "quality of service" is not used to express a degree of excellence in a comparative sense nor is it used in a quantitative sense for technical evaluations. In these cases a qualifying adjective (modifier) should be used.

Quality of Service Management (P1900.1 definition): Management of the network in order to conform with the QoS requirements for each application as agreed upon between the service provider and the end user.

Note 1 - Agreement between the service provider and user may be implicit, such as when the provider and user are related entities, or may be explicitly defined in a Service Level Agreement.
Note 2 - Network management systems accommodate different QoSs for distinct applications by prioritizing network traffic, as well as monitoring and maintaining the network as a whole.

Radio Environmental Maps (REM): REM is envisioned as an integrated space-time-frequency database consisting of multi-domain information, such as geographical features, available services, spectral regulations, locations and activities of radios, relevant policies, and experiences, that characterizes the radio environment for Cognitive Radio applications.

Radio Resource Management (RRM): The purpose of radio resource management (RRM) is to ensure the efficient use the available radio resources and to provide mechanisms that enable the radio access network to meet radio resource related requirements as enhanced support for end to end QoS, efficient support for transmission of higher layers, and support of load sharing and policy management across different Radio Access Technologies.

Reconfigurable Radio (RR) (P1900.1 definition): A type of radio whose functionality can be changed either through manual reconfiguration of radio modules or can be changed under software control. Software Defined Radio and Software Radio are both Reconfigurable Radios, as are Radios with less extensive support for reconfiguration.

Note 1 - Software reconfiguration control of such radios may involve any element of the radio communication network.

Note 2 - Manual reconfiguration of the radio includes the physical change or removal of hardware components

Software Defined Radio (SDR) (FCC Definition): A radio that includes a transmitter in which the operating parameters of frequency range, modulation type or maximum output power (either radiated or conducted), or the circumstances under which the transmitter operates in accordance with Commission rules, can be altered by making a change in software without making any changes to hardware components that affect the radio frequency emissions.

Software defined radio (SDR) (ITU-R Definition): A radio in which RF operating parameters including but not limited to frequency range, modulation type, or output power can be set or altered by software, and/or the technique by which this is achieved.

Note 1 - Excludes changes to operating parameters which occur during the normal pre-installed and predetermined operation of a radio according to a system specification or standard.

Note 2 - SDR is an implementation technique applicable to many radio technologies and standards.

Note 3 - Within the mobile service, SDR techniques are applicable to both transmitters and receivers.

Software defined radio (SDR) (P1900.1 definition): A type of radio in which some or all of the physical layer functions are software defined.

Note 1 - Radios in which the communications functions are implemented in software are considered Hardware Radios for regulatory purposes if the regulated emission or reception parameters cannot be changed in the field, post manufacture, without physically modifying the device. However, a device having *regulated parameters that can be changed without physical modification is considered a software defined radio, even if such change requires specialized equipment or proprietary procedures.*

Note 2 - This term represents an idealized abstraction that is useful in designating categories of radio devices (e.g., hardware radio, software defined radio, and cognitive radio) to which certain regulatory provisions or functional capabilities may apply. The term is also useful in describing the general evolution in the software reconfigurability of radio devices with hardware radio not being software reconfigurable and software defined radio being software reconfigurable. Software defined radios include software reconfigurable hardware such as microprocessors, digital signal processors, and field programmable gate arrays that are used with software to implement communications functions. The degree of software reconfigurability will depend on the radio implementation.

Software Radio (SR): Software Radio is the 'ideal', while the SDR constitutes the 'practical' form of an SR. The 'ideal' implementation of an SR receiver would be to attach an analogue to digital converter directly to the antenna. A general-purpose processor architecture would then read the converter output, and the software implementation would transform the stream of data from the converter to any other form. Vice versa, an 'ideal' transmitter would be just the mirror: software running on a general purpose processor would generate the digitised output stream, a digital to analogue converter would then transform this into analogue RF signals which in turn would be transmitted via the antenna.

A radio that implements communications functions primarily through software in conjunction with minimal hardware. Software radios are the ideal software defined radio in which digitization occurs at the antenna. Software radios can do an infinite number of things in contrast to hardware radios that can do only a limited number of things which are restricted by hardware complexity limitations.

Spatial Awareness (P1900.1 definition)

Awareness by a device of its relative orientation and position.

Note - Radios may use this knowledge to improve network performance and to control the Dynamic Spectrum Access process. For example, a radio may be able to use Spatial Awareness information to control the operation of an adaptive antenna and thereby reject undesired signals and enhance reception of desired signals.

Capability to geolocate a system or device through the use of mechanisms involving RF signals or related information, or network information.

Note - The cognitive application includes the selection and optimization of the techniques, signals and networks to use for geolocation. This may involve the use of some GPS signals, although the cognitive approach is more appropriate where GPS signals are totally or partially not available, and signals in the environment, specifically being used for communications purposes, or from networks or other specific users are used. It may also include information available, processed or unprocessed, from the network(s) to which the system or device has access.

Spectrum Access (P1900 definition**):** Ability to obtain or make use of the radio spectrum.
Note - Spectrum Access includes the attributes of frequency, location, time, power (spectral flux density) and angle of arrival. These attributes may be further characterized by additional parameters. For example modulation further characterizes the frequency attribute of spectrum access.

Spectrum Allocation: The assignment of a block of spectrum by the spectrum regulator to be exploited for a given service provided by an operator.

Spectrum Assignment: A way of distributing frequency resources among cells.

Spectrum Broker (P1900.1 definition): An entity, device, or device capability responsible for dynamic assignment of spectrum access rights.

Note - Typical spectrum broker scenarios:

A spectrum broker may lease parts of the frequency spectrum to specific parties under certain policy with or without time constraints.

A spectrum broker may be owned by the government radio regulators (specific to countries where applicable) or by private or independent organizations.

A spectrum broker may be a cognitive radio or a capability within a cognitive radio having limited authority to negotiate and issue dynamic spectrum access rights to other radios capable of dynamic spectrum access.

Spectral Efficiency: Performance metric that measures the amount of successfully delivered bits per unit of time and spectrum.

Spectral Efficiency (P900.1 definition): A general measure of how well a spectrum segment of interest is being utilized that is determined from the ratio of the benefits derived from the spectrum usage to the resource costs of providing those benefits.

Spectrum Management: Capturing the best available spectrum to meet user communication requirements.

Spectrum Management (P900.1 definition): The process of developing and executing policies, regulations, procedures, and techniques used to allocate, assign, and authorize frequencies in the radio spectrum to specific services, and users.

Note - Spectrum management is typically performed by governmental agencies or quasi-governmental entities. Non-governmental entities and individuals, including licensees (license holders) network managers and service providers also engage in spectrum management. Spectrum sharing is one of the components of spectrum management. Spectrum management seeks to maximize the utility derived from use of the radio spectrum. Historically, spectrum management has involved extensive preplanning and has ad difficulty adapting rapidly to changes in requirements and environmental conditions. The inability to dynamically react to change is an obstacle to maximizing utility.

Spectrum Mobility: the process of maintaining seamless communication requirements during the transition to better spectrum.

Spectrum Sensing: Spectrum sensing refers to the action of a wireless device measuring characteristics of received signals, which may include RF energy levels as part of the process of determining if a particular section of spectrum is occupied.

Sensing in the spectrum domain is the detection of some signal features indicating the presence (or absence) of other users/services. These can include signal energy, periodic features (pilots, preambles, chip rates), likely identity of the other users/services, estimation of interference-tolerance.

Spectrum Sensing (P1900 definition**):** The action of a radio measuring signal features.

Note - For instance, a radio engaging in dynamic spectrum access may use spectrum sensing to determine if a particular section of spectrum is occupied. Examples of some signal features that could be sensed include energy, bandwidth, periodic features (pilot 1 signals, preambles, chip rates), identity of transmission source, interference tolerance capabilities, and expected duration of spectrum usage.

Spectrum Sharing: Ability for different radio technologies to use the same portion of spectrum without creating harmful interferences to each other. The operation of the RATs may be co-channel or adjacent channel and may be constrained by technical provisions deduced from the results of compatibility studies between the two systems involved in the sharing scenario. See also: Dynamic Spectrum Sharing. Spectrum Sharing make it possible for several terminals or network nodes to communicate providing a fair spectrum scheduling method.

Spectrum Sharing (P1900 definition**)**: The application of technical methods and operational procedures to permit multiple users to coexist in the same region of spectrum.

Note - Coexistence may by achieved by numerous methods such as coordinating time usage (e.g., time sharing), geographic separation, frequency separation, directive antennas, orthogonal modulations, etc. In the past, the employment of these mechanisms has typically been on a static, preplanned basis. In advanced radio systems, the employment and configuration of these features is increasingly dynamic and may be implemented in real-time by the radio device or network in response to changing conditions and objectives.

Spectrum Sharing (secondary users in licensed spectrum): Spectrum sharing is the method where spectrum that has been assigned to a license holder is made available to other users on a secondary, non-interfering basis.

Spectrum Utilization (P1900.1 definition**)** The space denied to other potential users. Spectrum utilization may be defined as the product of the frequency bandwidth, the geometrical (geographic) space, and the time denied to other potential users:

$$U = B \times S \times T,$$

where U is the amount of spectrum space used (Hz × m^3 × s), B is the frequency bandwidth, S is the geometric space (desired and denied) and T is time.

Note 1 - The determination of the amount of bandwidth, space, and time occupied will be a function of the characteristics of other systems desiring to use or share the same spectrum and may involve numerous assumptions such as the level of protection to be provided or the propagation model used to determine signal loss. Consequently, the comparison of spectrum utilization values may only be meaningful between like systems where the assumed conditions are similar.

Note 2 - Transmitters and receivers both use spectrum space. Transmitters use spectrum space by denying the use of that space to certain receivers (other than the intended receiver) that would receive interference from the transmitter. This space is called "transmitter-denied space", or simply "transmitter space". Receivers use spectrum space by denying the use of nearby space to additional transmitters (assuming that the receiver is entitled to protection from interference). A transmitter operating in that space would cause *interference to the receiver's intended operation. This space is called "receiver denied-space", or simply "receiver space.*

Spectrum Utilization Efficiency (P1900.1 definition**)***:* The spectrum utilization efficiency is defined as the ratio of information transferred to the amount of spectrum utilization:

$SUE = M/U = \underline{M}/(B \times S \times T)$,

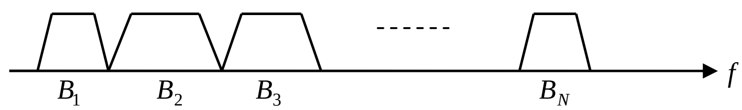
where M is the amount of information transferred, and U is the amount of spectrum utilization.

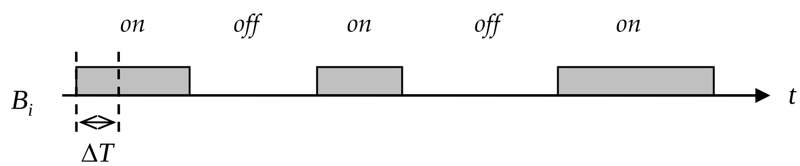
Note - Because the computation of SUE is primarily of interest in comparing the efficiency of similar types of systems, the quantity M should take the form most meaningful and convenient for the systems being compared. M could be in terms of bits/sec, Erlangs, analog channels, radar channels, etc.

White Space: frequency band allocated to a licensed service but not used locally (e.g. in time and/or space).

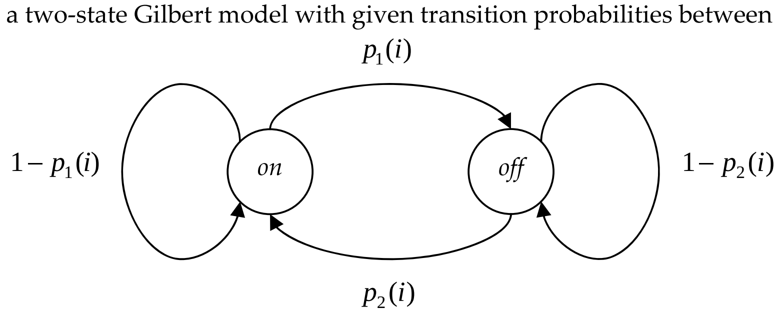
Annex II: Simple ON/OFF model

This annex aims at recalling some well known results that can be useful if the primary user's traffic can be modelled by a simple (Markov) On/Off process, especially from the point of view of the secondary user (what can be achieved as a secondary user). This relatively simple model assumes that the whole frequency band of interest is divided in a number N of sub-bands $B_1, B_2, \cdots, B_N$ which may have different widths; their activity is time varying, that means that a given band B_i can be occupied (someone is transmitting) or idle during each time slot ΔT as sketched below:





The model considers the state *on* if a band is occupied and *off* if nobody transmits in the band during the slot under consideration. With these notations the time activity of a given sub-band B_i can be modelled by a two-state Gilbert model with given transition probabilities between states:



$p_1(i)$ is the transition probability from state *on* to state *off* for the sub-band B_i, conversely for the transition probability $p_2(i)$ from state *off* to state *on*. The steady state probabilities P_{on}, P_{off} of a given sub-band B_i to be active or idle are then given by the classical formula [27]:

$$P_{on}(i) = \frac{p_2(i)}{p_1(i) + p_2(i)}, \quad P_{off}(i) = \frac{p_1(i)}{p_1(i) + p_2(i)}$$

Now the analytical statistics from this simple setting can be obtained. For instance, the number of active sub-bands B_i in a given time slot ΔT by use of the polynomial can be derived

$$P(X) = \prod_{i=1}^{N} \left(P_{off}(i) + X\, P_{on}(i) \right) = \sum_{j=0}^{N} A_j^{(N)} X^j$$

where $A_j^{(N)}$ is the probability of having j active sub-bands and $N-j$ idle ones. From this polynomial, for instance, the average number of active sub-bands in a time slot can be computed. Indeed, from the derivative $P'(X)=\sum_{j=0}^{N} j\times A_j^{(N)}\, X^{\,j-1}$ the following average value can be obtained as:

$$P'(1)=\sum_{j=0}^{N} j\times A_j^{(N)}$$

As $P(X)$ is a product of (simple) polynomial, its logarithmic derivative we can be also used to write:

$$\frac{P'(X)}{P(X)}=\sum_{i=1}^{N}\frac{P_{on}(i)}{P_{off}(i)+X\,P_{on}(i)} \Rightarrow \frac{P'(1)}{P(1)}=\sum_{i=1}^{N}\frac{P_{on}(i)}{P_{off}(i)+P_{on}(i)}=\sum_{i=1}^{N}P_{on}(i)$$

Finally, it is not necessary to compute the $A_j^{(N)}$ coefficients to obtain the average number of active sub-bands:

$$\sum_{j=0}^{N} j\times A_j^{(N)} = \sum_{i=1}^{N}\frac{p_2(i)}{p_1(i)+p_2(i)}$$

Moreover, if all sub-bands had the same bandwidth, the average free amount of spectrum available for an opportunistic use could also be derived.

Statistics for a given sub-band

The same approach can provide interesting results when considering a single sub-band B_i over a number of n successive time slots ΔT . To this the following definitions are introduced:

- $A(m,n)$ is the probability of having m active slots over n when the initial state is *on*.
- Likewise, $B(m,n)$ is the same probability when the initial state is *off*.
  These quantities can be gathered as polynomial coefficients:

$$A_n(X)=\sum_{m=0}^{n} A(m,n)\,X^{m}$$

$$B_n(X)=\sum_{m=0}^{n} B(m,n)\,X^{m}$$

Averaging these probabilities over the steady state probabilities of *on* and *off* states give the unconditional probability $P(m,n)$ of having m occupied slots over n consecutive slots:

$$P(m,n)=P_{on}\,A(m,n)+P_{off}\,B(m,n)$$

$$P_n(X)=\sum_{m=0}^{n} P(m,n)\,X^{m}=P_{on}\,A_n(X)+P_{off}\,B_n(X)$$

The probabilities $A(m,n)$ and $B(m,n)$ can be computed iteratively as sketched below. To gain insight on the procedure, first we begin with two consecutive time slots to obtain the four possible outcomes:

On	On	On	Off	Off	On	Off	Off

Then, by inspection, the following relationships are obtained:

$$\left.\begin{aligned} A(0,2) &= 0 \\ A(1,2) &= p_1 \\ A(2,2) &= 1 - p_1 \end{aligned}\right\} \Rightarrow A_2(X) = p_1\, X + (1-p_1)\, X^2$$

$$\left.\begin{aligned} B(0,2) &= 1 - p_2 \\ B(1,2) &= p_2 \\ B(2,2) &= 0 \end{aligned}\right\} \Rightarrow B_2(X) = (1-p_2) + p_2\, X$$

The probabilities of the four configurations over 3 consecutive slots beginning from *on* state are easily obtained:

On	On	On	On	On	Off	On	Off	On	On	Off	Off

$$\left.\begin{aligned} A(0,3) &= 0 \\ A(1,3) &= p_1\,(1-p_2) \\ A(2,3) &= p_1 p_2 + (1-p_1)\, p_1 \\ A(3,3) &= (1-p_1)^2 \end{aligned}\right\} \Rightarrow A_3(X) = p_1\,(1-p_2)\, X + \left[p_1 p_2 + (1-p_1)\, p_1\right] X^2 + (1-p_1)^2\, X^3$$

Likewise for the configurations beginning with a *off* state:

Off	On	On	Off	On	Off	Off	Off	On	Off	Off	Off

$$\left.\begin{aligned} B(0,3) &= (1-p_2)^2 \\ B(1,3) &= p_2 p_1 + (1-p_2)\, p_2 \\ B(2,3) &= p_2 (1-p_1) \\ B(3,3) &= 0 \end{aligned}\right\} \Rightarrow B_3(X) = (1-p_2)^2 + \left[p_2 p_1 + (1-p_2)\, p_2\right] X + p_2 (1-p_1)\, X^2$$

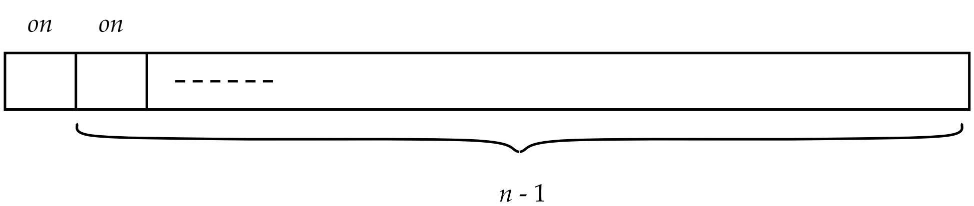
The reader can check that these two polynomials may also be written as

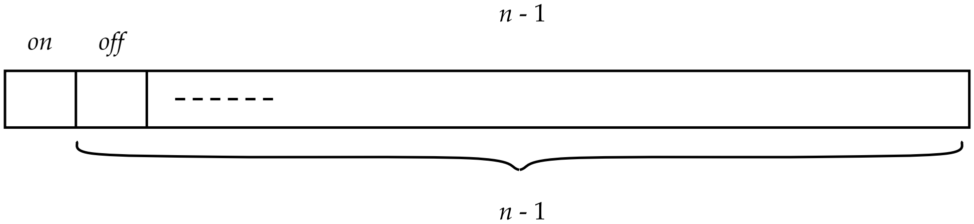
$$\begin{aligned} A_3(X) &= p_1 X\, B_2(X) + (1-p_1) X\, A_2(X) \\ B_3(X) &= p_2\, A_2(X) + (1-p_2)\, B_2(X) \end{aligned}$$

or under the matrix form:

$$\begin{bmatrix} A_3(X) \\ B_3(X) \end{bmatrix} = \begin{bmatrix} (1-p_1)X & p_1 X \\ p_2 & 1-p_2 \end{bmatrix} \times \begin{bmatrix} A_2(X) \\ B_2(X) \end{bmatrix}$$

This can be generalized as described in [27]; the $n-1$ consecutive time slots following the initial *on* state are separately enumerated whether they begin by a *on* or *off* state:





To have *m* active time slots beginning with an *on* state means having $m-1$ active slots in the $n-1$ remaining time slots; then accounting for the possible transitions between the first and second state this first recurrence can be obtained:

$$A(m,n) = (1-p_1)\,A(m-1,n-1) + p_1\,B(m-1,n-1)$$

Likewise for the $B(m,n)$ coefficients the same reasoning provides the following recurrence:

$$B(m,n) = p_2\,A(m,n-1) + (1-p_2)\,B(m,n-1)$$

These two recurrences can be written in a polynomial form:

$$A_n(X) = (1-p_1)\,X\,A_{n-1}(X) + p_1\,X\,B_{n-1}(X)$$
$$B_n(X) = p_2\,A_{n-1}(X) + (1-p_2)\,B_{n-1}(X)$$

Once again the recurrence can be written in a matrix form

$$\begin{bmatrix} A_n(X) \\ B_n(X) \end{bmatrix} = \begin{bmatrix} (1-p_1)X & p_1X \\ p_2 & 1-p_2 \end{bmatrix} \times \begin{bmatrix} A_{n-1}(X) \\ B_{n-1}(X) \end{bmatrix}$$

The initial conditions for the recurrences are given by:

$$\begin{cases} A(0,1) = 0 \\ B(0,1) = 1 \end{cases} \text{and} \begin{cases} A(1,1) = 1 \\ B(1,1) = 0 \end{cases}$$

Finally the following expression can be written

$$\begin{bmatrix} A_n(X) \\ B_n(X) \end{bmatrix} = \begin{bmatrix} (1-p_1)X & p_1X \\ p_2 & 1-p_2 \end{bmatrix}^{n-1} \times \begin{bmatrix} X \\ 1 \end{bmatrix}$$

The probabilities $P(m,n)$ are the coefficients of the polynomial $P_n(X)$ given by:

$$P_n(X) = \left[P_{on}, P_{off}\right] \times \begin{bmatrix} (1-p_1)X & p_1X \\ p_2 & 1-p_2 \end{bmatrix}^{n-1} \times \begin{bmatrix} X \\ 1 \end{bmatrix}$$

Example 1: comparison with the binomial distribution

The distribution $P(m,n)$ is generally (very) different from a binomial distribution on *n* trials with the active slot probability P_{on}, that is $P_{binomial}(m,n) = C_n^m\,{P_{on}}^m\,(1-P_{on})^{n-m}$, as depicted in the following picture (Figure 58) for $n = 50$ time slots and transition probabilities $p_1 = 0.2, p_2 = 0.3$. This basic example is an indication of the potential interest of the On/Off model to model the time occupancy of a frequency band. Nevertheless $P(m,n)$ does not give any indication of the way the occupied states are distributed: are they completely sparse or are they rather clustered with long idle periods between them? To this end the definitions of bursts and runs that have been introduced to model the distribution of errors in wireless channels [27] need to be considered.

Example 2: distribution of bursts or runs

A *burst* is defined a consecutive series of occupied states without idle states so that the channel cannot be accessed within the burst. Likewise a *run* is a succession of idle states without any occupied slot so that a run is a period within which a secondary user could use the resource. Furthermore, assuming that the longer the observation time the better the performance of the detection, it is clear that we are rather interested in runs above a given length or the complementary cumulated density function (CCDF):

$$\Pr\left[\text{run length} \geq n\right] = B(0,n) = \left(1-p_2\right)^{n-1}$$

Remark

This On/Off model assumes that the transition probabilities are the true ones, but we keep in mind that the secondary user may not know these probabilities. So we must enhance this model to take into account that the secondary user performs a detection (sensing) of the primary user and that this detection is not perfect, that means we should introduce the false alarm and non detection probabilities in the above model.

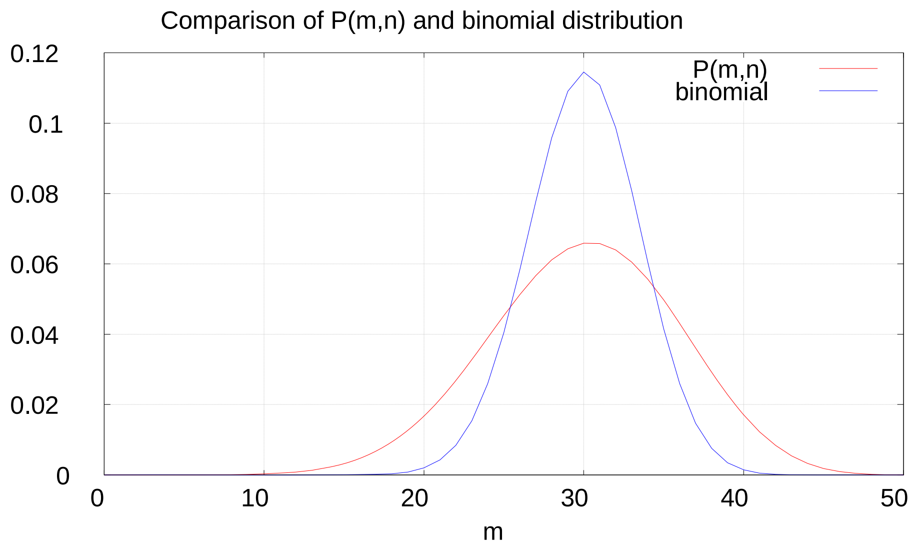


Figure 58. Comparison of P(m.n) and binomial distribution for n=50 and p_1=0.2 and p_2=0.3

Annex III: Patents Review

In this annex, some of the patents that are relevant to this project are listed. It is not an exhaustive list but selected ones that seem important are listed. It is to be noted that almost all of the patents are in "application" stage and not granted yet please see the suffixes. , It has to be emphasized that there are no IPRs that limit the scope of the FARMIR project. The relevant patents are grouped into four types based on the keywords used in search.

I. Cognitive Radio Spectrum Sensing
II. Distributed / Cooperative Spectrum Sensing
III. Radio Environment Map / Cognitive Radio Database
IV. Resource Allocation with Spectrum Sensing

I. Cognitive Radio Spectrum Sensing

Database	Keyword 1	Keyword 2	Hits
Aureka	"Cognitive Radio"	"Spectrum Sensing"	116
Espacenet	"Cognitive Radio"	"Spectrum Sensing"	82

A. ROBUST SENSING FOR DETECTING SIGNALS USING CORRELATION
EP2132880A1, Monisha GHOSH (PHILIPS)
To quickly and robustly detect the presence of an incumbent user and rapidly relinquish the spectrum to the incumbent user when necessary, carrier recovery is performed in a receiver of the secondary user's cognitive or software radio prior to performing correlation detection with an upsampled reference signal to correct for large frequency offsets and improve the performance of the correlation detector. To detect a received signal, a pilot value is added to a reference signal. The reference signal is upsampled to a sampling frequency of the received signal. The upsampled reference signal is correlated with a demodulated baseband signal to produce a correlation value. It is then determined whether the received signal is present if the correlation value is greater than a predetermined detection threshold value

- Correlation detection type, threshold based, pilot value added to a reference signal

B. OPPORTUNISTIC SPECTRUM SENSING OPTIMIZATION FOR A COMMUNICATION SYSTEM
US20090135744A1, Apoorv Chaudhri (MOTOROLA)
A combination of subscriber clustering and link interleaving provides a cognitive radio system (CR) with opportunities to sense an incumbent system's spectrum on secondary basis. The CR system uses clustering to identify out-of-band channels. The CR system uses link interleaving during a second mode of operation to sense and detect any incumbent on in-band channels. A list of out-band channels are sensed by clusters (0, 1, 2, 3) sequentially to generate a ranked list of potential channels for future use by the CR system. These out-of-band channels can be used opportunistically in case of in-band incumbent detection.

- Cluster based grouping of channels and ranking list of potential channels

C. SYSTEM AND METHOD FOR SCHEDULING OF SPECTRUM SENSING IN COGNITIVE RADIO SYSTEMS.
US2010003922A1, ZHOU XIANGWEI et al. (FUTUREWEI TECHNOLOGIES INC)

A method comprises sensing an availability of a spectrum band, computing a duration of an inter-sensing time block based on the availability of the spectrum band, and scheduling an occurrence of the spectrum sensing operation using the duration of the inter-sensing time block. Computing the duration of the inter-sensing time block based on the availability of the spectrum band allows for an optimization of communications of the cognitive radio system, thereby increasing spectral efficiency and reducing interference to licensed communications.

- Based on inter-sensing time block

D. METHOD AND APPARATUS FOR DISTRIBUTED SPECTRUM SENSING FOR WIRELESS COMMUNICATION.
US2009143019A1, STEPHEN SHELLHAMMER (Qualcomm)
Methods and apparatus for determining if a signal of interest, for example, a licensed signal having or exceeding a predetermined field strength, is present in a wireless spectrum and/or which facilitates such a determination are described. The signal of interest maybe, e.g., a television signal or a wireless microphone signal using licensed television spectrum. The predetermined field strength may be specified or by a government regulation or rule.

- Energy detector and threshold based, specifically for TV bands

E. METHOD AND APPARATUS RELATING TO SPECTRUM SENSING
WO2009148401, SELEN YNGVE et al. (ERICSSON)
The invention comprises a method and a corresponding apparatus. A candidate set of sensors that are available to participate in an occasion of cooperative spectrum sensing is obtained. For each sensor in the candidate set, its radial distance to a central coordinating node in a communication system is also obtained. A sequence of minimum radii is produced. For each minimum radius in the sequence, an accommodation number is determined. The accommodation number associated with a minimum radius is the greatest number of sensors that can be placed on circle having this radius without a probability that all these sensors are mutually uncorrelated falling below a design probability threshold. Sensors from the candidate set are then selectively added to an active set of sensors based on the minimum radii, the corresponding accommodation numbers and the obtained radial distances.

- Candidate sensors based on radial distance is used to collect uncorrelated sensing data

F. SYSTEM, APPARATUS, AND METHOD FOR A TWO-STAGE MECHANISM FOR QUIET PERIOD MANAGEMENT IN SPECTRUM AGILE RADIO NETWORKS
EP1989902A2, Carlo CORDEIRO (PHILIPS)
The present invention is a system, base station /customer premise equipment apparatus, and method for a two-stage quiet-period management mechanism that provides the required protection to incumbents (primary spectrum users) while supporting the desired QoS of secondary users participating in a cognitive radio network. In the first stage, a simple fast sensing is done (e.g., energy detection) by all devices in the network. Depending on the result of the fast sensing, the second and possibly longer stage, herein termed fine sensing, is performed.

- Two stage sensing (Fast and long-time)

G. SPECTRUM-SENSING ALGORITHMS AND METHODS
US20080080604A1, Youngsik Hur
Spectrum-sensing algorithms and methods may be provided for use in cognitive radios and other applications. The spectrum-sensing algorithms and methods may include receiving an input spectrum having a plurality of channels, performing a coarse scan of the plurality of channels of the input spectrum to determine one or more occupied candidate channels and vacant candidate channels, where the coarse scan is associated with a first resolution bandwidth and a first frequency sweep increment, performing a fine scan of the occupied candidate channels and the vacant candidate channels to determine actually occupied channels and actually vacant channels, where the fine scan is

associated with a second resolution bandwidth and a second frequency sweep increment, and storing an indication of the actually occupied channels and the actually vacant channels

- Coarse / Fine searching.

Basic Report: Documents By Top Assignees

source document list: **Temp Doc List (3)**

Assignee	Doc Count	Percentage
UNKNOWN	19	7.9%
MOTOROLA INC	17	7.0%
UNIV HONG KONG SCIENCE & TECHN	12	5.0%
KONINKL PHILIPS ELECTRONICS NV	11	4.6%
SAMSUNG ELECTRONICS CO LTD	8	3.3%
BEN LETAIEF KHALED	7	2.9%
ZHANG WEI	7	2.9%
NOKIA CORP	6	2.5%
ST MICROELECTRONICS INC	6	2.5%
CHAUDHRI APOORV	4	1.7%
Number of assignments in Top 10 assignees	**97**	
Total number of assignments	**242**	
Number of documents after filter	**116**	
Total number of documents in group	**116**	

II. Cooperative / Distributed Spectrum Sensing

Database	Keyword 1	Keyword 2	Hits
Aureka	"Distributed"	"Spectrum Sensing"	203
Aureka	"Cooperative"	"Spectrum Sensing"	15

A. METHOD, APPARATUS AND COMPUTER PROGRAM FOR SENSING SPECTRUM IN A COGNITIVE RADIO ENVIRONMENT

US2009253376, ILKONEN PETRI *et al*. (NOKIA)

To find frequency slots over which a cognitive radio can send an opportunistic transmission, a wideband spectrum is searched with a lower resolution to identify bandwidth slices having low or no signal levels. The identified bandwidth slices are searched with a higher resolution and candidate frequency slices are selected as those bandwidth slices having the least signal levels after the higher resolution searching, and ranked from the lowest signal level to the highest. A spectrum detection algorithm is executed on the selected candidate frequency slices in the order of the rank until it is decided that one of them has sufficiently free spectrum. A transmission is then opportunistically sent on the decided candidate frequency slice. Ongoing to the searching, intermittent signals are detected and a band about them is searched with the lower resolution to determine if the band about the detected intermittent signal is an identified bandwidth slice

- Selecting a channel with higher resolution and iteratively repeating this process

B. COMMUNICATION SYSTEM FOR EXCHANGING SPECTRUM SENSING MEASUREMENTS THROUGH A DROP BOX AND METHOD OF USING SAME
US2009245119, KUFFNER STEPHEN *et al*. (MOTOROLA)
A communications system and method for exchanging spectrum usage information through a drop box includes one or more central stations that defines a region of operation. A central drop box is associated with the central station for providing a database of spectrum usage information. Stations using the communications system may submit information regarding spectrum usage to the central drop box that affects the region of operation for providing the most efficient and non-interfering uses of the frequency spectrum.

- A drop-box (server) is set up for exchanging spectrum sensing information

C. DISTRIBUTED SPECTRUM SENSING
WO2009115957, PANDHARIPANDE ASHISH VIJAY *et al*. (PHILIPS)
In summary, the invention relates to a device, a system, a method and a computer program for spectrum sensing. A detection procedure for detecting a signal of interest or an event by using a plurality of sensing devices capable of communicating with a central unit is proposed. The sensing devices can compute soft detection metrics and communicate this information to a central unit, where the information may be used to make a final detection decision using a certain specified rule. The signaling overhead of the proposed approach can be of the same order as that of a hard signaling approach. However, the proposed approach may achieve a better detection performance.

- A soft decision locally and final detection decision at central unit

D. DISTRIBUTED SCHEDULING OF QUIET-PERIOD FOR IN-SERVICE CHANNEL MONITORING
WO2009069069A2, Jianfeng WANG (PHILIPS)
In a distributed-control cognitive radio network, each secondary user in a network broadcasts parameters that indicate the minimum quiet-period sensing demand for regular quiet-periods that the device requires for reliable detection of a primary user. Each device in the network adjusts its quiet-period sensing rate to accommodate the highest minimum sensing demand, thereby providing optimal efficiency relative to quiet-period support while assuring that all devices in the network are provided at least their minimum quiet-period sensing demand. Both the interval between regular quiet-periods and the duration of these quiet-periods are negotiated among the devices on the network. A quiet-period index is used to synchronize all of the devices to a common time base. Techniques are also provided for efficient coordination of on-demand quiet-period requests, and for supporting different quiet-period schedules for multiple classes of primary users.

- Quiet-period management to negotiate sensing information

E. METHOD FOR DETECTING UNUSED FREQUENCY BANDS IN COGNITIVE RADIO NETWORK
EP1942690A2, Koon Hoo Teo (MITSUBISHI ELECTRIC)
A method detects unused frequency bands in a cognitive radio network. Multiple frequency bands for RF signals are sensed using an antenna array including a plurality of elements coupled to a receive RF chain, in which the plurality of elements are individually controllable. For each frequency band, multiple spatial directions are sensed for the RF signals using the antenna array. A particular frequency band and a particular direction and a particular time slot are assigned as an available frequency band, an available direction and a particular time slot for transmitting RF signals in a cognitive radio if the RF signals are not sensed in the particular spatial direction for the particular frequency band, and in which the RF signals are transmitted by a transmit chain connected to the antenna array.

F. SPACE-TIME-FREQUENCY SENSING OF RF SPECTRUM IN COGNITIVE RADIOS
US7610036B2, Koon Hoo Teo (MITSUBISHI ELECTRIC)

A method detects unused frequency bands in a cognitive radio network. Multiple frequency bands for RF signals are sensed using an antenna array including a plurality of elements coupled to a receive RF chain, in which the plurality of elements are individually controllable. For each frequency band, multiple spatial directions are sensed for the RF signals using the antenna array. A particular frequency band and a particular direction and a particular time slot are assigned as an available frequency band, an available direction and a particular time slot for transmitting RF signals in a cognitive radio if the RF signals are not sensed in the particular spatial direction for the particular frequency band, and in which the RF signals are transmitted by a transmit chain connected to the antenna array.

G. ROBUST COOPERATIVE SPECTRUM SENSING FOR COGNITIVE RADIOS
WO2009101537, Khaled Ben Letaief (UNIV HONG KONG SCIENCE & TECHN)
The disclosed subject matter relates to communicatively coupled cognitive radio systems, devices, and methodologies facilitating utilization by secondary users of portions of spectral bands unused by primarily users. This utilization can be achieved by cooperative spectrum sensing employing ST coding and/or SF coding for transmit diversity. Further, cooperative spectrum sensing can be improved by employing relay diversity with or without algebraic coding. A threshold probability of false alarm can be reduced by applying transmit diversity with space time coding and/or space frequency coding. Further, relay diversity can be employed to compensate for reduced sensing diversity order were some nodes in a cooperative spectrum sensing system cannot report directly. Algebraic coding can be combined with relay diversity to decrease the threshold probability of false alarm in relay diversity systems while maintaining high levels of sensing diversity order.

H. CLUSTER-BASED COOPERATIVE SPECTRUM SENSING IN COGNITIVE RADIO SYSTEMS
US20080261639A1, Chunhua SUN (UNIV HONG KONG SCIENCE & TECHN)
Cluster-based cooperative spectrum sensing is provided for cognitive radio systems. For each cluster of cognitive users, a cluster head is determined. Each cluster head collects energies of a reporting channel measured by the cognitive users within the cluster and decides whether a primary user is absent from a given spectrum. A common receiver then aggregates the cluster-level decisions made by the cluster heads, and makes a decision across multiple, or all of, the clusters whether the primary user is absent based on a fusion function of the cluster-level decisions. If the primary (licensed) user is absent, then secondary (unlicensed) users may utilize the spectrum.

- Cluster-based cooperative spectrum sensing method
- Aggregating the sensing information in cluster-head for cluster-level decisions.

I. SYSTEM AND METHOD FOR UNSYNCHRONIZED COOPERATIVE SPECTRUM SENSING IN COGNITIVE RADIO NODES
US20100062718A1, Xiangwei Zhou
A method comprises receiving spectrum sensing information from a plurality of communications nodes, computing for each communications node in the plurality of communications nodes, a likelihood ratio based on spectrum sensing information provided by the communications node, combining the likelihood ratios, and computing a decision value based on the combined likelihood ratio. Each communications node determines its respective spectrum sensing information at a time unrelated to times when other communications nodes determine their spectrum sensing information.

- Based on individual sensing information and computing a decision value based on combined likelihood of the communicating node.

III. Radio Environment Map / CR Database

Database	Keyword 1	Keyword 2	Hits
Aureka	"Radio" AND "Environment"	"Map"	307
Epacenet	"Radio" AND "Environment"	"Map"	70
Aureka	"Cognitive"	"Database"	62
Epacenet	"Cognitive"	"Database"	12

A. WIRELESS DATA COMMUNICATION SYSTEM AND METHOD FOR PROVIDING WIRELESS DATA SERVICE TO SDR TERMINAL
US2010029297 (A1) KIM JUN SIK et al. (ELECTRONICS AND TELECOMM Korea)
A wireless data communication system includes a software defined radio (SDR) terminal having a wireless map, and accessing a desired wireless data service using the wireless map, wherein the wireless map includes GPS location information, information on wireless data services available at a current location of the SDR terminal based on the GPS location information and information on wireless connection software components for each wireless data service selected by the SDR terminal. The wireless data communication system further includes a base station for providing a wireless connection environment, an authentication center for authenticating the SDR terminal, a download server for providing the wireless connection software component to the SDR terminal, and a location-based service server for providing the wireless map to the SDR terminal.

B. COGNITION MODELS FOR WIRELESS COMMUNICATION SYSTEMS AND METHOD AND APPARATUS FOR OPTIMAL UTILIZATION OF A RADIO CHANNEL BASED ON COGNITION MODEL DATA
US7076246B2**,** Prabhakar Chitrapu (INTERDIGITAL TECH CORP)
Classes of cognition models which may include: 1) Radio Environment models, 2) Mobility models and 3) Application/User Context models are utilized in a wireless communications network. Radio Environment models represent the physical aspects of the radio environment, such as shadowing losses, multi-path propagation, interference and noise levels, etc. Mobility models represent users motion, in terms of geo-coordinates and/or logical identifiers, such as street names etc. as well as speed of user terminal etc. The context model represents the present state and dynamics of each of these application processes within itself and between multiple application processes. These data are employed to optimize network performance

C. METHOD AND APPARATUS FOR FRAME BASED RESOURCE SHARING IN COGNITIVE RADIO COMMUNICATION SYSTEM
US2010009692 (A1), SHAN CHENG et al. (SAMSUNG)
A frame structure, a method, and an apparatus for inter-frame resource sharing in a Cognitive Ratio (CR) communication system are provided. An apparatus for sharing a channel in an environment where a plurality of CR communication systems coexist, constitutes a Superframe Control Header (SCH), in one superframe, that includes a frame allocation MAP for frame information allocated to a Base Station (BS), with respect to each BS, and transmits and receives the SCH at the start frame of the frames allocated to the BSs

D. METHOD FOR GENERATING A RADIO MAP OF AN ENVIRONMENT AND RADIO COMMUNICATION SYSTEM BEING CONTROLLED ON THE BASIS OF A RADIO MAP GENERATED BY THIS METHOD

WO2009144030 (A2), BAUMANN ALEXANDER et al. (SIEMENS)

A method for generating a radio map of an environment starts with an initial radio map, used as current radio map in a first step. The radio map is then stepwise adapted by amending a current radio map by help of a measurement up-date of this current radio map, yielding an amended radio map in each step, using the amended radio map of the preceding step as current radio map of the current step. The measurement update is based on measurements made available by localizing a radio device in the environment using the current radio map. The accuracy of the localization is thereby improved stepwise by using amended radio maps, and the accuracy of the radio maps is improved by using measurements made available from an improved localization of radio devices.

E. SPECTRUM MANAGEMENT SYSTEM FOR MUNICIPAL SPECTRUM USING GUIDED COGNITIVE RADIO

US2010041339(A1), MILLER II ROBERT RAYMOND

A system and method for assigning a frequency to an access point in a wireless network comprising a plurality of access points is described. The system and method includes accessing a rule-base to obtain a set of rules for the wireless network, accessing a license database to obtain information about relevant wireless nodes in a region, creating a list of possible primary node frequencies from a list of frequencies associated with primary wireless nodes in the license database, creating a list of possible secondary node frequencies from a list of frequencies associated with secondary wireless nodes in the license database, identifying a list of clear frequencies from a set of unused frequencies, selecting a frequency from frequencies in the lists of possible primary node frequencies, possible secondary node frequencies, and clear frequencies and registering the frequency in the license database

F. MOBILE RADIO COMMUNICATION SYSTEM AND RADIO COMMUNICATION METHOD

WO2009104689(A1), ALTINTAS ONUR (TOYOTA)

In a mobile radio communication system of the cognitive radio method, a database device has a use state table indicating a probability that each frequency band is used for each period of time and for each location. An on-vehicle terminal acquires a frequency band having the highest probability that the band is empty at the current time and the current location according to the use state table and performs a radio communication by using the frequency band. The use state table is preferably created by a statistical process using the database device which acquires the use states of frequency bands of various locations and times by using respective vehicles as probe cars. Thus, it is possible to detect the frequency of the empty state in a short time.

G. METHOD OF OPERATING A COGNITIVE RADIO DEVICE AND COGNITIVE RADIO DEVICE

US2009180359(A1), WALTER SIEGFRIED (ALCATEL LUCENT)

The invention relates to a method of operating a cognitive radio device, particularly a mobile terminal, which is capable of establishing radio communications with a further radio device, particularly a base station of a communications network and/or a further mobile terminal. The inventive method is characterized by: providing a communication parameter database local to said cognitive radio device, wherein said communication parameter database comprises communication parameters related to geographic locations, determining a geographic location of said cognitive radio device, and by choosing one or more communication parameters for a future radio communication depending on said communication parameter database and the determined location of the cognitive radio device.

H. METHOD AND APPARATUS FOR SPECTRUM SHARING BETWEEN AN INCUMBENT COMMUNICATION SYSTEM AND A COGNITIVE RADIO SYSTEM

WO2009018300(A1), GURNEY DAVID et al. (MOTOROLA)

Efficient frequency spectrum sharing between at least one incumbent communication system(s) and at least one cognitive radio (CR) system is provided. The incumbent system's system parameters and

CR system's operational requirements are copied to a mirrored database. The mirrored database is controlled by a either a central authority or a database manager having delegated authority. The mirrored database is accessed by the CR system. The mirrored database can be modified and updated by the central authority or delegated database manager to correct for interference detected in the incumbent system caused by the cognitive radio system. The cognitive radio system utilizes the updated mirrored database to avoid interfering with the incumbent system to determine CR system operating parameters thus enhancing the ability to share spectrum.

I. COGNITIVE COMMUNICATION SYSTEM, DATABASE DEVICE USED IN THE SYSTEM, AND WIRELESS COMMUNICATION APPARATUS
JP2007184850(A), TOMIOKA TAZUKO (TOSHIBA)
PROBLEM TO BE SOLVED: To determine a frequency when a radio apparatus of a cognitive radio starts communication by correctly grasping not only the use situation of a radio wave that can be detected by the radio apparatus but also the use situation of a frequency of the reaching range of the radio wave. ; SOLUTION: In the cognitive communication system, the database device for frequency use situation management for a wireless communication system for performing cognitive radio is made into a network and hierarchized. A first database device included in a wireless communication system is located at a lower rank of the hierarchy. As a result, the wireless communication system can obtain information that can not be independently known and information collected by other database devices from second database.

Basic Report: Documents By Top Assignees

source document list: **Temp Doc List (7)** Print-Friendly

Assignee	Doc Count	Percentage
MOTOROLA INC	21	16.0%
UNKNOWN	6	4.6%
GURNEY DAVID P	4	3.1%
INTERDIGITAL TECH CORP	4	3.1%
AYOUB RAMY S	3	2.3%
COMMISSARIAT ENERGIE ATOMIQUE	3	2.3%
NOKIA CORP	3	2.3%
ALCATEL LUCENT	2	1.5%
BELCEA JOHN M	2	1.5%
BOEING CO	2	1.5%
Number of assignments in Top 10 assignees	**50**	
Total number of assignments	**131**	
Number of documents after filter	**62**	
Total number of documents in group	**62**	

IV. Resource Allocation with Spectrum Sensing

Database	Keyword 1	Keyword 2	Hits
Aureka	"Cognitive" "Spectrum Sensing"	"Allocation"	19
Espacenet	"Cognitive" "Spectrum Sensing"	"Allocation"	12

A. DYNAMIC ALLOCATION OF SPECTRUM SENSING RESOURCES IN COGNITIVE RADIO NETWORKS
US2009247201, YE ZHUAN (MOTOROLA)
A method, wireless controller, and information processing system are provided to dynamically allocate spectrum sensing resources. A first input including available sensing session time for performing spectrum sensing with respect to one or more primary systems is received. A second input including a set of communication channels to be monitored in the spectrum sensing session is received. A third input including detection constraints associated with a plurality of available sensing nodes in a secondary network for performing the spectrum sensing is received. Spectrum sensing resources are dynamically allocated among a set of the plurality of available sensing nodes based on the first, second, and third inputs.

B. DYNAMIC TIME-SPECTRUM BLOCK ALLOCATION FOR COGNITIVE RADIO NETWORKS
WO2008144323A1, Paramvir BAHL, (MICROSOFT CORP)
Dynamic time-spectrum block allocation for cognitive radio networks is described. In one implementation, without need for a central controller, peer wireless nodes collaboratively sense local utilization of a communication spectrum and collaboratively share white spaces for communication links between the nodes. Sharing local views of the spectrum utilization with each other allows the nodes to dynamically allocate non-overlapping time-frequency blocks to the communication links between the nodes for efficiently utilizing the white spaces. The blocks are sized to optimally pack the available white spaces. The nodes regularly readjust the bandwidth and other parameters of all reserved blocks in response to demand, so that packing of the blocks in available white spaces maintains a fair distribution of the overall bandwidth of the white spaces among active communication links, minimizes finishing time of all communications, reduces contention overhead among the nodes contending for the white spaces, and maintains non-overlapping blocks.

- Without central controller, peer-peer collaboration spectrum sensing
- Nodes re-adjust the bandwidth allocation adaptively

C. DISTRIBUTED MULTI-CHANNEL COGNITIVE MAC PROTOCOL
US20090258603A1, Kaveh Ghaboosi (NOKIA)
A method includes sending a message from a first cognitive radio apparatus to at least one second cognitive radio apparatus, the message being sent over a first communication channel and containing an advertisement of at least one second communication channel for use in sending data from the first cognitive radio apparatus to the at least one second cognitive radio apparatus. The method further includes receiving a reply from the at least one second cognitive radio apparatus over the first communication channel, where the reply contains one of an acceptance of one of the at least one second communication channels, a rejection of the at least one second communication channel and an advertisement of at least one third communication channel, or a rejection of the at least one second communication channel without an advertisement of at least one third communication channel. The method further includes transmitting the data from the first cognitive radio apparatus to the at least one second cognitive radio apparatus over an agreed upon one of the second or third channels.

D. METHOD FOR SPECTRUM COLLABORATION IN DYNAMIC FREQUENCY-HOPPING WIRELESS REGIONAL AREA NETWORK
WO2008133453(A1), CHENG JINXIA (SAMSUNG)
The method for spectrum collaboration in dynamic frequency- hopping wireless regional area network comprising steps of: CPE in all WRANs performing spectrum sensing and feeding relevant idle channel information back to respective control base stations; a WRAN with high priority determining spectrum resource allocation for WRAN system in spectrum collision state. At the same time, significant problems that greater time delay caused by the lack of free idle channel resource for adjacent WRANs, can be effectively avoided. Therefore, it efficiently helps the operator to effectively consolidate the spectrum resource to improve both communication quality and reliability within the coverage of the whole WRAN.

E. METHOD AND SYSTEM FOR OPTIMIZING THE USE OF THE RADIO SPECTRUM AND COMPUTER PROGRAM PRODUCT THEREFOR
US2007053410 (A1), EP1750467 (A1), MAHONEN PETRI H, MELPIGNANO DIEGO
A system for scanning a frequency spectrum to detect usage thereof includes an ultra-wideband receiver for performing the scanning, and cooperates with a spectrum usage estimator module and a radio controller unit. The spectrum usage estimator module derives from the scanning performed via the ultra-wideband receiver information as to usage of individual bands in the frequency spectrum. The radio controller unit controls operation of a radio cognitive system as a function of the information as to usage of individual bands in the frequency spectrum as derived by the spectrum usage estimator module. The radio cognitive system operates over unused bands in the frequency spectrum.

F. METHOD AND SYSTEM FOR DYNAMIC SPECTRUM ALLOCATION, AND COMPUTER PROGRAM PRODUCT THEREFOR
EP1750466 (B1), MAHONEN PETRI H, MELPIGNANO DIEGO
A communication network (ON) including a set of user terminals (UE1, UE2) such as a cellular network or a WLAN includes a system for dynamically controlling spectrum usage. The system includes: - a sensing functionality (BS1, BS2; UE1, UE2) for sensing spectrum usage within the area covered by said communication network (ON); - a policy server (PS) configured for producing, as a function of the spectrum usage as sensed, spectrum usage policies for the communication network (ON); and - a broadcasting arrangement (BS1, BS2; UE1, UE2) for broadcasting the spectrum usage policies to the user terminals (UE1, UE2). A preferred use of the invention is within the framework of Cognitive Radio systems.

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Glossary and Definitions

Term	Description
3GPP	3rd Generation Partnership Project
ACK	Acknowledge
A/D	Analog to Digital
ADC	Analog to Digital Converter
AGC	Automatic gain control
AOA	Angle-of-Arrival,
ARM	Available Resource Map
ASM	Advanced Spectrum Management
ATSC DTV	Advanced Television Systems Committee- Digital Television
AWGN	Additive White Gaussian Noise
BC	Backup Channel
BOF	BORPH Object File
BORPH	Berkeley Operating System for ReProgrammable Hardware
BS	Base Station
BTS	Base Station Transceiver System
CAB	Coordination Access Bands
C-MAC	Cognitive MAC
CBP	Coexistence Beacon Protocol
CCC	Common Control Channel
Ccdf	Complementary Cumulated Density Function
CCN	Cognitive Control Network
CDMA	Code Division Multiple Access
CE	Cognitive Engine
CEPT	European Conference of Postal and Telecommunications Administrations
CH	Channel or Radio Channel
CMN	Cognitive Mesh Network
CPE	Customer Premises Equipment
CPC	Cognitive Pilot Channel
CPU	Central Processing Unit
CR	Cognitive Radio
CRAHNs	CR ad hoc networks
CRBS	Cognitive Radio Base Station
CRLB	Cramer-Rao Lower Bound
CRM	Cognitive Resource Management
CRS	Cognitive Radio Shell also Cognitive Radio Systems
CSCC	Common Spectrum Coordination Channel
CSMA/CA	Collision Sense Multiple Access with Collision Avoidance
CTS	Clear to Send
CRS	Cognitive Radio Systems
CRU	Cognitive Radio User
CWN	Composite Wireless Network
DAC	Digital to Analog Converter
DARPA	Defense Advanced Research Projects Agency (USA)

Term	Description
DVB-T	Digital Video Broadcasting – Terrestrial,
DC	Duty Cycle
DCA	Distributed Channel Assignment
DCSM	Device Centric Spectrum Management scheme
DIMSUMNet	Dynamic Intelligent Management of Spectrum for Ubiquitous Mobile-access Network
DOSS	Dynamic Open Spectrum Sharing
DOSS-MAC	Dynamic Open Spectrum Sharing MAC
DP	Data Processors
D-QDCR	Distributed QoS Based Dynamic Channel Reservation
DS	Downstream
DSA	Dynamic Spectrum Allocation or Dynamic Spectrum Access
DSANs	Dynamic Spectrum Access Networks
DSAP	Dynamic Spectrum Access Protocol
DS-CDMA	Direct Sequence-Code Division Multiple Access
DSP	Digital Signal Processor
DSRC	Dedicated Short Range Communication
DSSS	Direct Sequence Spread Spectrum
DTB	Data Transmission Band
DTP	Data Transfer Period
DTV	Digital Television
DUB-MAC	Dual Unlicensed Band MAC
DVD	Digital Versatile Disc
DySPAN	Dynamic Spectrum Access Networks
ECC	Electronic Communications Committee
EIRP	Effective Isotropic Radiated Power
EMC	Electromagnetic Compatibility
ENOB	Effective Number of Bits
FCC	Federal Communications Commission
FDD	Frequency Division Multiplexing
FDOA	Frequency-Difference-of-Arrival
FE	Front End
FFT	Fast Fourier Transform
FOA	Frequency-of-Arrival
FPGA	Field-Programmable Gate Array
GLS	Geo-Location System
GMSK	Gaussian Minimum Shift Keying
GPIB	General Purpose Interface Bus
GPS	Global Position System
HA	Hardware Accelerators
HC-MAC	Hardware Constrained MAC
HD-MAC	Heterogeneous Distributed MAC
HSS	Hierarchical Spectrum Sharing
HSSN	Hierarchical Spectrum Sharing Network
HTTP	Hypertext Transfer Protocol
ICMP	Internet Control Message Protocol
IDRP	Incumbent Detection Recovery Protocol

Term	Description
IEEE	Institute of Electrical and Electronic Engineering
IF	Intermediate Frequency
ILP	Integer Linear Programming
ISM	Industrial Scientific and Medical band
ITU	International Telecommunication Union
IOREG	Input/Output Register
I/O	Input/Output
JRRM	Joint Radio Resource Management
JTAG	Joint Test Action Group
KNOWS	Kognitiv Networking Over White Spaces project
k-NN algorihtm	k-nearest neighbours algorithm
LAN	Local Area Network
LB	Local Bargaining
LLC	Link Layer Control
LMS	Least Mean Square
LNA	Low noise amplifier
LO	Local Oscillator
LOS	Line-of-Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MC-ADP	Multi Channel Asynchronous Distributed Pricing
MGT	Multi-Gigabit interface
MIMO	Multiple Input Multiple Output
ML	Maximum Likelihood
NAV	Network Allocation Vector
NE	Nash Equilibrium
NG	Negotiation
NLOS	Non Line-of-Sight
NSF	National Science Foundation (USA)
NRM	Network Reconfiguration Manager
NTIA	National Telecommunications & Information Administration (USA)
OFDM	Orthogonal Frequency Division Multiplexing
OSM	Operator spectrum manager
OS-MAC	Opportunistic Spectrum MAC
OSSIE	Open-Source SCA Implementation - Embedded
PCS	Personal Communication System
PDA	Personal Digital Assistant
PDF	Probability Density Function
PE	Policy Engine
PFA	Probability of False Alarm
PHY	Physical Layer
PSD	Power Spectral Density
PSK	Phase Shift Keying
PLE	Position-Location Estimation
PLL	Phase locked loop
POMDP	Partially Observable Markov Decision Process
PTT	Push To Talk

Term	Description
PU	Primary User
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
QoS	Quality-of-Service
RAM	Resource Allocation Matrix
RAN	Radio Access Networks
RAT	Radio Access Technology
RC	Rendezvous Channel
RE	Radio Enabler
REA	Radio-Environment Awareness
REM	Radio Environmental Maps
RF	Radio Frequency
RMC	RAN measurement collector
RRC	RAN reconfiguration controller
RRM	Radio Resource Management
RRS	Reconfigurable Radio Systems
RSS	Received Signal Strength
RST	Ready to Sent
RBW	Resolution Band-Width
SAM	Spectrum Allocation Map
SCA	Software Communications Architecture
SCB	Signalling and Control Band
SC-ADP	Single Channel - Asynchronous Distributed Pricing
SCH	Superframe Control Header
SC/MC-ADP	Single Channel and Multi Channel Asynchronous Distributed Pricing
SDR	Software Defined Radio
SDSE	Strongly Dominant Strategy Equilibrium
SFDR	Spurious-Free Dynamic Range
SML	Service Management Layer
SNR	Signal to Noise Ratio
SPI	Serial Peripheral Interface
SPS	Spectrum Policy Server
SRAC	Single-Radio Adaptive Channel
SSC	Shared Spectrum Company
SYN-MAC	Synchronized MAC
TC	Technical Committee
TCP	Transport Control Protocol
TDMA	Time Division Multiple Access
TDOA	Time-Difference-of-Arrival
TOA	Time-of-Arrival,
TRM	Terminal Reconfiguration Manager
TSS	Two-Stage Sensing
TV	Television
TVWS	TV White Space
UMTS	Universal Mobile Telecommunications System
UHF	Ultra High Frequency
UDP	User Datagram Proto

Term	Description
US	Upstream
USB	Universal Serial Bus
UWB	Ultra Wide Band
VBW	Video Band-Width
VCO	Variable Controlled Oscillator
VH	Virtual Header
VT-CORNET	Virginia Tech Cognitive Radio Network
V2V	Vehicle-To-Vehicle
WAPECS	Wireless Access Policy for Electronic Communications Services
WiFi	Wireless Fidelity
WiNC2R	Winlab Network Centric Cognitive Radio) testbed
WISP	Wireless Internet Service Provider
WLAN	Wireless Local Area Network
WRAN	Wireless Regional Area Network also Wireless Radio Access Network
WRC	World Radiocommunication Conference
WS	White Spaces
XG	NeXt Generation
XOA	X-of -Arrival