# Development and implementation of technology – neutral spectrum sharing protocols

*State of the Art Assessment*

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**Abstract**

In recent years, radio spectrum has become an increasingly scarce and valuable resource. The proliferation of wireless devices, the emergence of smartphones and the enormous increase in mobile data traffic call for the development of new, more efficient methods and technologies to use the radio spectrum. Sharing spectrum between different classes of users has been identified as a potential means to relieve the problem of spectrum scarcity, with Cognitive Radio being the most prominent enabling technology.

This report intends to provide an assessment of the state-of-the-art in development and implementation of technology-neutral spectrum sharing protocols. A spectrum sharing protocol is a set of rules or a framework defining how radio spectrum may be accessed by different users. As spectrum sharing is predominantly handled within the link layer the focus of this report is on this part of the cognitive radio protocol stack.

# Content

# List of acronyms

| Acronym | Meaning |
|---------|---------|
| AFA | Adaptive Frequency Agility |
| AMRCC | Adaptive Multiple Rendezvous Control Channel |
| APC | Adaptive Power Control |
| CC | Control Channel |
| CCC | Common Control Channel |
| CCC | Cognitive Control Channel |
| CPC | Cognitive Pilot Channel |
| CR | Cognitive Radio |
| CRAHN | Cognitive Radio Ad-Hoc Network |
| CRN | Cognitive Radio Network |
| CRS | Cognitive Radio System |
| CSMA/CA | Carrier Sense Multiple Access/Collision Avoidance |
| CSMA/CD | Carrier Sense Multiple Access/Collision Detection |
| CUS | Collective Use of Spectrum |
| DAA | Detect-And-Avoid |
| DCC | Dedicated Control Channel |
| DFS | Dynamic Frequency Selection |
| DSA | Dynamic Spectrum Access |
| ECC | European Communications Committee |
| ETSI | European Telecommunications Standards Institute |
| FH | Frequency Hopping |
| FHCC | Frequency Hopping Control Channel |
| FHSS | Frequency Hopping Spread Spectrum |
| IEEE | Institute of Electrical and Electronics Engineers |
| IETF | Internet Engineering Task Force |
| ISM | Industrial, Scientific, Medical |
| ITU-R | International Telecommunication Union - Radiocommunication Sector |
| LAN | Local Area Network |
| LBT | Listen-Before-Talk |
| LDC | Low Duty Cycle |
| MAC | Media Access Control |
| MNO | Mobile Network Operator |
| MRCC | Multiple Rendezvous Control Channel |
| NSP | Network Setup Problem |
| OSA | Opportunistic Spectrum Access |
| OSI | Open Systems Interconnection |
| PHY | Physical Layer |
| PU | Primary User |
| QoS | Quality of Service |
| RAT | Radio Access Technology |

| | |
|---|---|
| RFE | Radio Front-End |
| RRS | Reconfigurable Radio Systems |
| RSPG | Radio Spectrum Policy Group |
| RSPP | Radio Spectrum Policy Programme |
| SDR | Software-Defined Radio |
| SP | Split Phase |
| SU | Secondary User |
| TA | Time Agility |
| TCP/IP | Transfer Control protocol/Internet protocol |
| TPC | Transmit Power Control |
| TVWS | Television White Space |
| UWB | Ultra Wide Band |
| WLAN | Wireless Local Area Network |
| WPAN | Wireless Personal Area Network |
| WRAN | Wireless Regional Area Network |

# Introduction

## Context of the analysis/Study

In recent years, radio spectrum has become an increasingly scarce and valuable resource. The proliferation of wireless devices and services, the emergence of smartphones and the enormous increase in mobile data traffic call for the development of new, more efficient methods and technologies to use the radio spectrum. Sharing spectrum between different classes of users has been identified as a potential means to relieve the problem of spectrum scarcity.

Promoting the shared use of radio spectrum is one of the main objectives of the Radio Spectrum Policy Program (RSPP) of the European Commission [1]. The need for a more efficient use of spectrum through spectrum sharing is highlighted in various studies such as the Report of Collective Use of Spectrum (CUS) [2] by the Radio Spectrum Policy Group (RSPG) [3], an advisory body to the Commission consisting of high-level representatives from national administrations.

### Aim of the study

The aim of this study is to provide DG CONNECT B.4 with well-founded background information on the state-of-the-art in research and implementation of technology-neutral spectrum sharing protocols in support of future regulatory decisions.

## How the analysis/Study was carried out

First, the following information categories corresponding to the various key aspects of spectrum-sharing protocols were defined:

- Spectrum sharing concepts and mechanisms
- Spectrum sharing in Cognitive Radio (CR) Systems
- Classification of CR protocols
- Research and standardisation activities
- Test and evaluation platforms and activities

Data was collected from various sources:

- Web search: More than 250 scientific papers, articles, and reports on spectrum sensing were reviewed
- Inputs from standardisation bodies: Latest information on spectrum sensing standardisation was collected from ETSI TC RRS, IEEE
- Inputs from Research projects
- Personal discussions with experts from companies, research institutions, and universities

The collected information was grouped and analysed according to the categories defined above.

## Results of the analysis - Summary

Although significant research efforts have been made during the past ten years the development and implementation of technology-neutral spectrum sharing protocols is still in an early stage. The majority of studies address mobile cognitive radio ad-hoc networks, and dozens of different protocols have been proposed. One of the main challenges in this area is to develop a robust control and coordination channel that enables an exchange of information between cognitive nodes.

Current standardisation work, in contrast, focuses on a centralised approach to enable the coexistence of heterogeneous networks, in particular for geolocation-based TV white Spaces (TVWS) applications that rely on a common Cognitive Pilot Channel. Even in this case, however, there has been no agreement on the protocol and control channel implementation.

Most studies rely on simulations; there is very little experimental verification. Numerous, mostly small-scale testbeds exist but there are no common rules or performance metrics to evaluate CR protocol and system performance.

## Basic Definitions

- Cognitive Radio Node: A terminal, access point or base station that is able to dynamically change its transmission or reception parameters by using information collected or sensed from its external environment.

- Cognitive Radio Network (CRN): A network composed of Cognitive Radio Nodes.

- Control Channel (CCC): A channel used to distribute information other than data among the Cognitive Radio Nodes.

- Primary User (PU): A radio device licensed to operate in a specific part of the radio spectrum.

- Secondary User (SU): A radio device operating - on a non-interference basis - in the radio spectrum allocated to a primary (licensed) user.

- Geo-Location Data Base (GLDB): A database that stores the position and the characteristics (e.g. transmission power of the primary users) through REMs.

- White Space: A part of the radio spectrum, which is available for a radiocommunication application (service, system) at a given time in a given geographical area on a non-interfering / non-protected basis with regard to primary services and other services with a higher priority on a national basis" [2].

- TV White Spaces (TVWS): Spectrum bands that are licensed to digital TV broadcast but not used locally.

# Spectrum sharing

## Objectives and definitions

The main objective of spectrum sharing is to use a given portion of the radio spectrum as efficiently as possible whilst enabling the best possible performance for all participating systems.

 "Spectrum sharing" is a rather broad term, so in the first step we will define the meaning of "Spectrum sharing" in the context of this document.

In 2001 the ITU-R defined general principles and methods for sharing spectrum between radio communication services, covering both inter-service and intra-service sharing [4]. This generic definition includes practically all sharing mechanisms that fall into the categories of frequency, spatial location, time and signal separation.

| Frequency separation | Spatial separation | Time separation | Signal separation |
|---|---|---|---|
| Channelling plans | Geographical shared allocations | Duty cycle control | Signal coding and processing |
| Band segmentation | Site separation | Dynamic real-time frequency assignment | Forward error correction (FEC) |
| Frequency agile systems | Antenna system characteristics: | Time division multiple access (TDMA) | Interference rejection |
| Dynamic real-time frequency assignment | Adaptive antenna (smart antenna) | | Code division multiple access (CDMA) |
| Frequency division multiple access (FDMA) | Antenna polarization discrimination | | Spread spectrum: |
| Control of emission spectrum characteristics | Antenna pattern discrimination | | Direct sequence |
| Dynamic variable partitioning | Space diversity | | Frequency hopping |
| Frequency tolerance limitation | Antenna angle or pattern diversity | | Pulsed FM |
| Demand assignment multiple access (DAMA) | Space division multiple access (SDMA) | | Interference power/ bandwidth adjustments: |
| Frequency diversity | Physical barriers and site shielding | | Co-channel |
| | | | Dynamic transmitter level control |
| | | | Power flux-density (pfd) limitation and spectral power flux-density (spfd) limitation (energy dispersal) |
| | | | Modulation complexity |
| | | | Coded modulation |
| | | | Adaptive signal processing |
| | | | Antenna polarization |

Table 1: Spectrum sharing methods – ITU-R [4]

The European Radio Spectrum Policy Group (RSPG), an advisory body to the European Commission, adopted a more specific definition [5]:

*Spectrum sharing is defined as the simultaneous usage of a specific radio frequency band in a specific geographical area by a number of independent entities, leveraged through mechanisms other than traditional multiple- and random-access techniques. To put it simply, spectrum sharing consists in a common exploitation of frequencies among several operators: the end users of these operators can access the services of their respective mobile network operator (MNO) through all the frequencies that are shared in the access network.*

The above definition implies that access to shared spectrum will be provided in a dynamic way. This dynamic spectrum access (DSA) can be done either in a predetermined, allocation-based or in an opportunistic way. DSA thus encompasses a number of different models (Figure 1). The key technology that is supposed to enable DSA is Cognitive Radio (CR).  Following an overview of spectrum sharing concepts and principles this report will therefore focus on advanced spectrum sharing mechanisms enabled by CR.
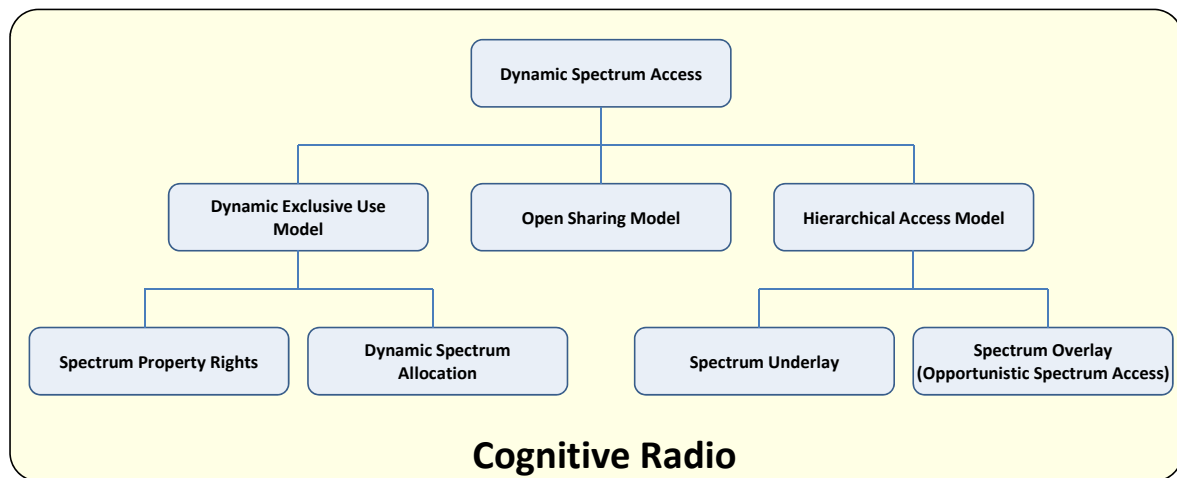
Figure 1: A taxonomy of Dynamic Spectrum Access (adapted from [6])

## Concepts and principles

### Classification

Spectrum sharing can be realised in various ways. Peha [7] differentiates between two basic operational models for spectrum sharing arrangements.

1.  Cooperation or coexistence.

2.  Sharing among equals or primary-secondary sharing.

In a model based on cooperation, all devices, even those under different administrative control must communicate and cooperate with each other to avoid mutual interference. This requires a common protocol which must be supported by all systems in the band. With a coexistence model, devices try to avoid interference without explicit signalling [7].

The second operational model is based on user prioritisation, i.e. it defines whether spectrum is shared among equals or between primary and secondary users. In the first case, all devices have equal rights, and typically a certain degree of flexibility about how to behave in the presence of peers. In the latter case, some systems have the right to operate as primary spectrum users, and secondary devices are only allowed to operate if they do not create interference to a primary system [7].

In both models, devices may operate under a licensed or unlicensed regime. A licensed system must get permission from the regulator to operate within a given frequency band. The licensing process is an opportunity for the regulator to ensure exclusive access to a block of spectrum if it wishes, which is strong protection from the problems of interference and congestion. In contrast, unlicensed systems need no permission from the regulator to deploy a device. Devices can typically be deployed anywhere, which means there is no limit to the number of devices that might be operating in a given location [7].

These spectrum sharing arrangements can be realized by various technical approaches which can broadly be categorized as either adaptive or non-adaptive mechanisms.

Non-adaptive mechanisms do not consider their spectrum environment but rely on specific signal properties to limit interference. These mechanisms are not designed to avoid but to limit interference to a level acceptable for other users and thus fall into the coexistence category.

Examples for non-adaptive spectrum sharing mechanisms are: *Low Duty Cycle* (LDC), *Frequency Hopping Spread Spectrum* (FHSS), *Transmit Power Control* (TPC), and *Aloha*.
*Code Division Multiple Access* (CDMA) and the initial implementations of *Ultra-Wide Band* (UWB) are examples for non-adaptive spectrum underlay technologies [8]. Systems based on these technologies operate at very low power levels, typically below the noise floor or the sensitivity limits of other (primary) users.

Spectrum sensing mechanisms obviously require radio systems that are capable of sensing their RF environment. According to [9], radio systems can be grouped into three categories: Aware, adaptive, and cognitive systems.

An *Aware Radio* is capable of surveying its RF environment and process the received information, for instance for channel, interference or signal estimation [9]. According to this definition, such radio can only employ non-adaptive spectrum sharing mechanisms such as the ones listed above.

An *Adaptive Radio* has the ability to sense its RF environment as well as autonomously change its operating parameters, such as frequency, instantaneous bandwidth, modulation, error correction code, and equalization. A frequency hopping spread spectrum system (FHSS), for instance, is not considered adaptive since its hopping patterns are predetermined. If, however, the FHSS is capable of changing its hop pattern to reduce collisions, it can be considered an adaptive radio [9]. Examples for adaptive spectrum sharing techniques are *Listen-Before-Talk* (LBT), *Detect-And-Avoid* (DAA), *Dynamic Frequency Selection* (DFS), *Adaptive Frequency Agility* (AFA), Time Agility (TA) and *Adaptive Power Control* (APC). These techniques are sometimes also referred to as reactive techniques [10].

A *Cognitive Radio* has the ability to sense and to adapt to its RF environment, as well as to learn. It senses its spectrum environment, identifies unoccupied or unused spectrum, establishes communication links in this spectrum, and moves to another band if a prioritised user (re-)enters that band. The adaptive capability of these radios improves as they learn more about their environment [9].

A special case is the geolocation database concept that is deployed in TV White Spaces (TVWS) [11]. In this case the nodes are stationary and have no or very limited sensing capabilities. A central entity keeps track of the positions of the cognitive nodes and allocates frequencies to each node according to a pre-established radio environment map.

Spectrum sharing schemes in which no or very little explicit information is exchanged between the entities involved, such as Aloha, LBT and DAA, are sometimes referred to as spectrum sharing etiquettes [12]. Devices operating under an etiquette do not have to understand each other's signalling. Etiquettes are therefore simple, but they are also sub-optimal in terms of medium utilization. Optimal medium utilization requires the exchange of information such that participating stations have the same view of the status of the shared medium. The exchange of this information requires a protocol: with this addition, a spectrum sharing etiquette becomes a medium access control protocol [12].

| Sharing mechanism | Sharing arrangement | |
| --- | --- | --- |
| | Cooperation | Coexistence |
| Non-adaptive | | ● |
| Adaptive | | ● |
| Cognitive | ● | ● |

Table 2: Spectrum sharing arrangements and mechanisms
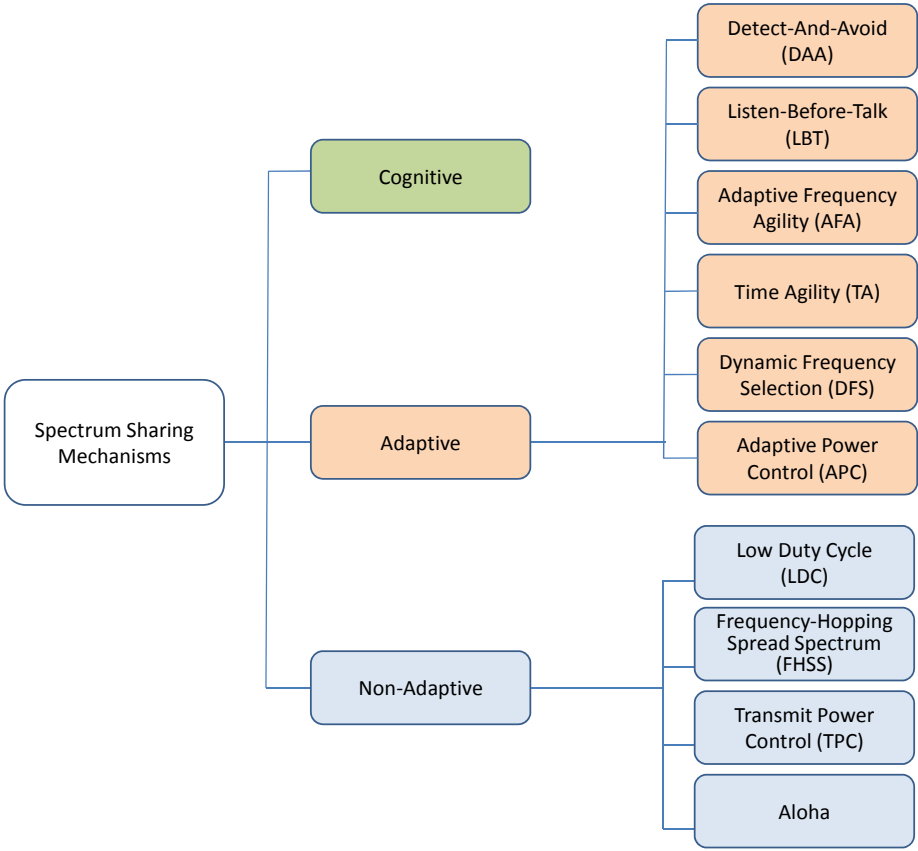


Figure 2: A classification of Spectrum ShariNG Mechanisms (selection)

## Cognitive Radio

The four main functions of cognitive radios can be summarized as follows [13]:

- ▸ Spectrum sensing: Determine which portion of the spectrum is available and detect the presence of licensed users when a user operates in a licensed band.

- ▸ Spectrum management: Select the best available channel (frequency) for communication.

- ▸ Spectrum sharing: Coordinate fair spectrum access to this channel with other users.

- ▸ Spectrum mobility: Vacate the channel when a licensed user is detected while still maintaining seamless communication requirements during the transition to a better piece of spectrum.

These tasks require a large amount of network and channel state information that must be shared simultaneously between multiple layers of the network model[1] (Figure 3). The spectrum sharing function is predominantly handled by the lower layers of the network model, in particular the link layer.
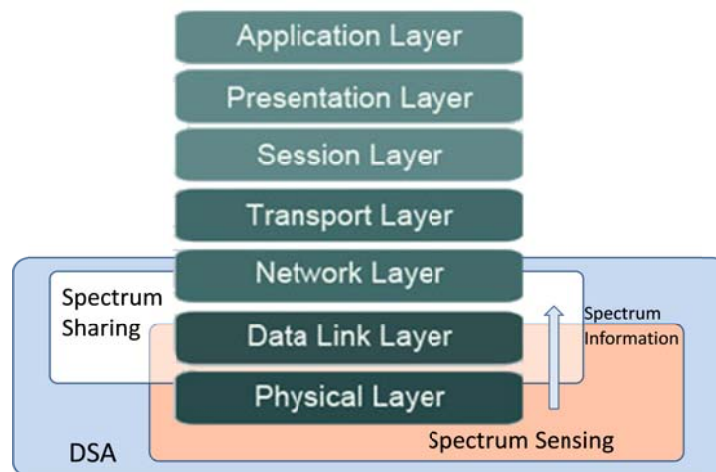


Figure 3: Spectrum Sensing and Spectrum Sharing in the OSI Model (adapted from [14])

### Cognitive Radio protocols

In communications, a protocol is a set of rules governing the communication between two or more parties.

In CR systems, multiple protocols on different layers are involved, e.g. cooperation protocols (link layer), end-to-end networking and spectrum-aware routing protocols (network and transport layer) [15] [16], and application layer protocols such as PAWS [17] which runs between cognitive nodes/masters and a geolocation database. The nature and number of the protocols used depend on the radio environment (network heterogeneity), the cognitive network architecture (primary-secondary, distributed or centralised, sensing only, sensing plus geolocation, geolocation only,

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[1] In literature, references to both the OSI and the TCP/IP model can be found. In the context of this document, the differences between those models are not relevant.

autonomous or cooperative/distributed sensing, etc.). The design of the main cognitive radio functionalities, i.e., spectrum sensing, spectrum management, spectrum handoff and spectrum sharing, requires the cooperation between different communication layers. Exchanging data among these layers is the case book definition of cross-layer design [13], a recent protocol definition technique that jointly optimizes the behaviour of two layers of the protocol stack that have no common interface [18].

## Spectrum Sharing Protocols

A spectrum sharing protocol is a set of rules or a framework defining how radio spectrum may be accessed by different users. As spectrum sharing is predominantly handled within the link layer (Figure 4) we focus our study on this part of the cognitive radio protocol stack.
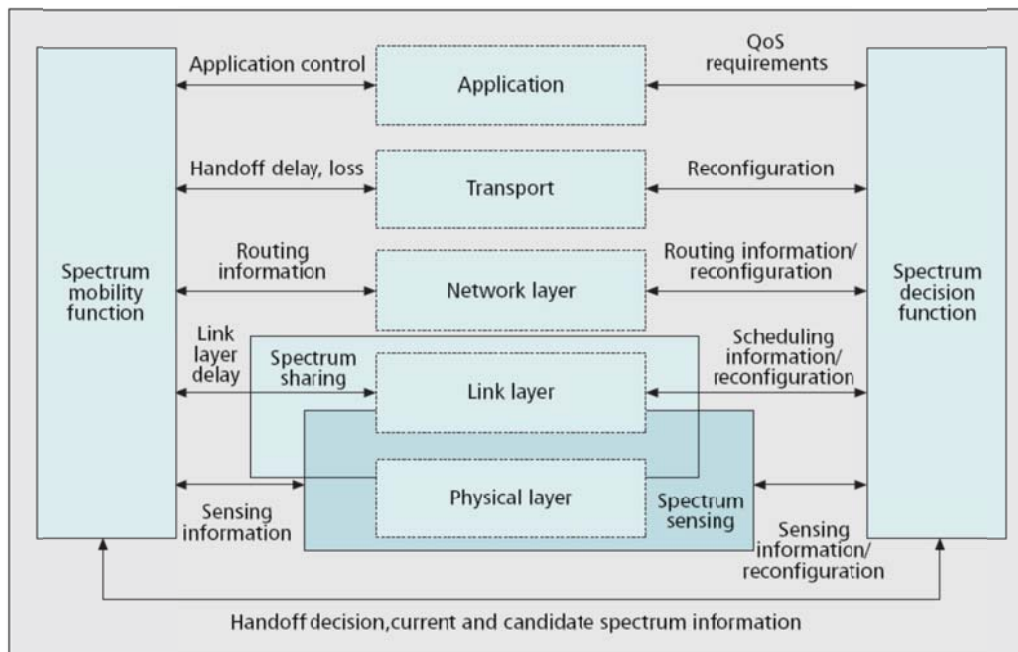


Figure 4: Spectrum management framework for cognitive radio networks [19]

The protocol responsible for identifying and allocating suitable communication channels, setting up communication between nodes, and maximising spectrum efficiency in a fair way resides in the MAC sub-layer of the link layer. It is therefore usually referred to as MAC protocol.

### Single- vs. multi-channel MACs

In a conventional, single-channel MAC scenario, multiple nodes share a common medium (i.e. a channel) and try to communicate over this shared channel. If more than two stations try to access the shared channel simultaneously, collision occurs. In other words, stations contend for the limited resource. Numerous protocols have been developed to resolve this problem, including *Carrier Sense Multiple Access with Collision Detection* (CSMA/CD) for local area networks (LAN) and *Carrier Sense Multiple Access/Collision Avoidance* (CSMA/CA) for wireless LAN (WLAN) [20]. A multi-channel MAC, in contrast, utilises multiple orthogonal channels in parallel (see Figure 5).
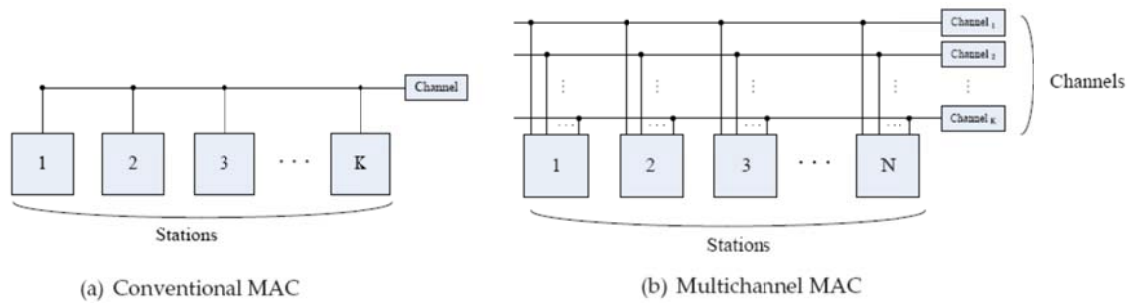
Figure 5: Conventional single-channel MAC vs. multi-channel MAC [20]

In wireless multichannel systems the MAC has two main functions, selecting the communication channel, and avoiding collisions and resolving contention.

Multi-channel MAC protocols for ad-hoc wireless networks represented a first step in the development of MAC protocols for cognitive radio [21]. These protocols address similar problems; they operate in a multichannel context, and they face the multi-channel hidden terminal problem. A cognitive radio may exploit, however, more sophisticated sensing functionalities; it distinguishes between different types of users, such as primary and secondary users, and provides protection to primary users' transmissions. The number of channels available at each user is fixed in a conventional multi-channel network, while it varies with time and space in a cognitive network. Furthermore, the time-scale in which a cognitive radio operates is very different from that of an ad-hoc radio: secondary users must regularly sense their radio environment, and must rapidly adapt their behaviour to achieve QoS and comply with interference constraints [21].

The *multi-channel hidden terminal problem* occurs when a node that is ready to transmit does not notice an on-going reception by its neighbouring node because different nodes can operate on different channels. As a consequence, the former node may start transmitting on the channel used by its receiving neighbour node. The resulting data packet collisions will have a negative impact on network performance [22].

Another critical issue in distributed cognitive radio networks is the so-called *multi-channel exposed terminal problem*. This problem occurs when a node that is ready to transmit discovers that its neighbouring nodes are transmitting data in certain channels, the former node will remove those channels from its list of available channels. As a result, the number of channels available to this node is reduced, and network throughput will be degraded [22].

**MAC protocol classification**

The design of a MAC protocol for CR has to consider several choices which depend on the target application(s) and/or scenario(s). These design choices allow the spectrum sharing techniques to be classified into many categories. A MAC protocol may belong to one or more of these categories, designed to work under certain constraints for certain scenarios [23]. In scientific literature cognitive MAC Protocols are classified in numerous ways.

### By architecture

Network architectures can be classified as centralized/infrastructure-based, distributed/ad-hoc, or clustered.

In a centralized architecture, a central entity controls spectrum allocation and access procedures. Each node in the network forwards its state and requirements to the central entity, which decides on the spectrum allocation and access schedule, and informs all participating nodes about the schedule [23].

In a distributed architecture, there is no fixed network infrastructure or central controller, and the participating entities have to organize themselves and build a spectrum access map in a distributed manner. These are typically used in Cognitive Radio Ad-Hoc Networks (CRAHNs), where the construction of an infrastructure is not feasible [23].

In a clustered architecture several cognitive nodes form a group, with one node acting as cluster head that coordinates spectrum access [24].

Centralized networks such as IEEE 802.22 WRAN in which a central entity manages the SUs are also referred to as *single-hop networks*. By contrast, *multi-hop networks* are distributed networks in which information needs to be relayed over multiple wireless links [25].

### By cooperation type

CR nodes can operate in a cooperative or in a non-cooperative manner.

In cooperative networks, cognitive nodes consider the presence and state of other nodes during the allocation process. Each node shares its information with its neighbours, its cluster, or a central entity. Cooperation can take place within the network (intra-network cooperation), or between different networks (inter-network cooperation) [26]. Inter-network cooperation can involve both secondary and primary networks.

In non-cooperative networks, the users do not share any information. Instead the nodes access the spectrum independently according to both local observation and statistics, using pre-determined rules [19].

### By Spectrum utilisation strategy

Based on their spectrum utilisation strategies, DSA protocols can be divided into two categories, single-channel and multi-channel protocols. While in single-channel protocols each source-destination pair of nodes can only use one channel for their data transmissions, multi-channel protocols allow the source and destination nodes to utilise multiple channels simultaneously. In [22], the multi-channel protocols are further divided into two sub-categories, hardware-based and software-based protocols. Hardware-based protocols require each cognitive node to be equipped with multiple radio front-ends (RFEs), each of which operates on one channel. On the contrary, software-based protocols applying the channel aggregation technique only need one RFE per node [22].

### By spectrum sharing mode

Depending on their spectrum sharing mode, MAC protocols can be categorized as overlay or underlay protocols [22] [27] [28]. With overlay protocols, SUs can access spectrum at times or in

locations with no PU activity while in underlay systems SUs may permanently access spectrum occupied by PUs [22]. There are also hybrid overlay-underlay approaches [27] [29]. It has to be noted that the above terminology is not universal. Some authors [30] use the term *interweaved* for mechanisms that are categorised as *overlay* in this report, and the term *overlay* for mechanisms that allow collisions between primary and secondary users transmissions (i.e., in the way LDC or CSMA/CD do).

### *By control channel implementation*

In CR networks, the dynamic and opportunistic use of spectrum requires that the cognitive nodes are able to find each other to establish a link. This process is also known as "rendezvous". In single-rendezvous protocols, the rendezvous between a transmitter and its receiver can take place on at most one channel at any time while multiple-rendezvous protocols enable several rendezvous to take place in different channels simultaneously, thereby mitigating control channel congestion [31].

A rendezvous requires the exchange of control and status information between the nodes. This exchange is done via a Control Channel (CC), frequently implemented in the form of a Dedicated or Common Control Channel (DCC/CCC).

A CCC can be realised as an in-band or out-of-band channel, and as an overlay or underlay channel, e.g. using UWB [32]. An in-band CCC may be interfered to by PU activity, and requires a setup phase every time the CCC has been disrupted. Out-of-band signalling can be achieved either through a licensed channel reserved for CCC use or through an unlicensed channel. [23].  A licensed channel is interference proof while an unlicensed channel may suffer from interference.

In [23] the following CC classes are defined:

▶ A *global control channel* is present throughout the network and can be used for signalling by all nodes.

▶ *Local control channels* may be used with clustered network architectures. The grouping of nodes may be based on their physical proximity, or the spectrum usage conditions. A local control channel is assumed to exist in such clusters and may be used for all the nodes in the same cluster.

▶ *Configurable control channels* are locally and temporarily created by a group of participating nodes using an available channel. No cluster-heads or group leaders are assumed to control spectrum access in the MAC schemes implementing such a channel.

▶ If no dedicated control channel can be configured, nodes may use an available channel for both data and control packets.

Local and configurable CCs are also referred to as non-dedicated CCs [33].

The use of a DCC simplifies the rendezvous process but may not be feasible in many opportunistic spectrum sharing scenarios due to the dynamically changing availability of all channels, including the control channel. Furthermore, the CCC concept suffers from problems concerning scalability (control channel saturation) and security (jamming by malicious users) [34]. To address these problems, non-dedicated [33] or non-common control channels, such as channel hopping [35] and split-phase control channels [31] have been proposed.

*Split-phase* protocols divide time frames into two parts, a control phase and a data phase. During the control phase each terminal overhears control messages to be aware of the network status. In the data phase, transmissions are performed. Hence, free data channels are wasted during the control phase, and system efficiency is reduced, while the control channel can be used for data transmissions during the data phase [21]. A further disadvantage is the need for synchronisation across the CR network [31].

The *Frequency Hopping Control Channel* (FHCC) concept has the advantage of using all channels for transmission and control, whereas a DCC is used exclusively for transferring control information. CR users hop across all licensed channels according to a predefined channel hopping sequence. During hopping, a transmitter-receiver pair exchanges control information to decide which channels to use for data transmission. When they successfully exchange control information, the communicating CR users stop hopping and start data transmission. Once done, both transmitter and receiver resynchronize with the hopping sequence. The main drawback of FHCC is its requirement for stringent time/channel synchronization between CR users [36].

A relatively recent CC implementation is *Multiple Rendezvous Control Channel* (MRCC) [37]. With MRCC, multiple nodes can exchange control information at the same time using all available channels. Each node knows the hopping patterns of its one-hop neighbours. Such hopping pattern is based on the seed of a pseudorandom generator. Once the seed of the receiver is known, the sender can follow the intended receiver on its hopping sequence. MRCC randomly spreads both control and data exchanges across all channels. As a result, MRCC is robust against unpredictable PU activities. However, MRCC also requires a more stringent synchronization between the hopping users since they have to keep track of the hopping times of their one-hop neighbours. In contrast to FHCC, it allows one to exchange more than one message during the control sequence.

A comparison of Multi-channel MAC CC implementations is presented in [20] (Figure 6).
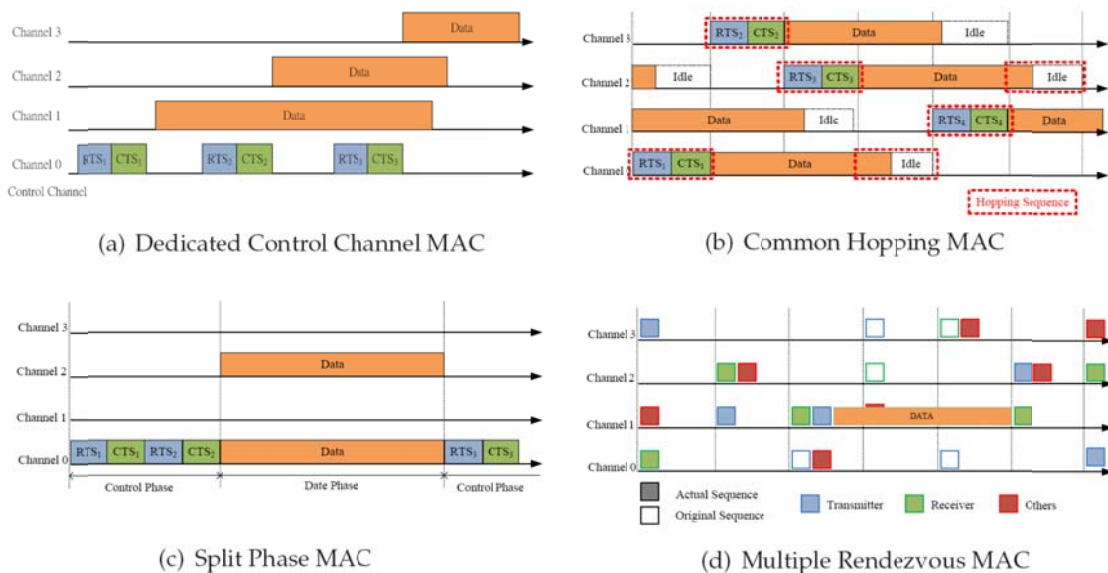


Figure 6: Multi-channel MAC Control Channel implementations [20]

Another example for realising a CC in a centralised network is the Cognitive Pilot Channel (CPC). CPC is a solution proposed by the E2R research project [38] for providing coordination and control between heterogeneous wireless networks by means of one or more dedicated and pre-defined "pilot" channels. CPC has been adopted by several standards bodies, namely the IEEE P1900.4 group [39], and ETSI [40]. CPC is an implementation of what ETSI and the IEEE refer to as the Cognitive Control Channel (also using the CCC acronym) concept [40] [41].

There are several radio access technology (RAT)-independent implementations of these Cognitive Control Channels, for instance through the IETF Diameter protocol, the 3GPP ANDSF service discovery protocol, the IEEE 802.21 protocol, or distributed agents [42]. All these are higher-layer protocols that rely on the availability of a certain type of connectivity (i.e., IP connectivity) between cognitive nodes [42].

### By channel access type

CR nodes can access the channel or channels either at random times, during defined time slots, or using a combination of both. MAC protocols can therefore be categorized as *Random Access protocols*, *Time-slotted protocols*, and *Hybrid protocols.*

*Random Access protocols* do not require time synchronization, and are generally based on the CSMA/CA principle. The cognitive node monitors the spectrum to detect transmissions from other users and transmits after a back-off period to prevent simultaneous transmissions. Random access protocols are also referred to as *contention-based protocols* [43].

*Time-slotted protocols*: These MAC protocols require network-wide synchronization, with defined time slots for both the control channel and data transmission.

*Hybrid protocols* use a partially slotted transmission, in which the control signalling generally occurs over synchronized time slots [23]. However, the following data transmission 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 users in the network. Within each control or data period, access to the channel may be completely random [44].

CR networks using random access protocols are also referred to as asynchronous networks, those using time-slotted access protocols as synchronous networks [45].

### By RF front-end count

Cognitive nodes may feature one or multiple RFEs. The number of RFEs usually depends on the type of control channel that is implemented. A CCC scheme does not require time synchronization, hence, in order to avoid that network nodes miss control messages, a dedicated transceiver is used for the common channel [21]. To work effectively, a CCC requires at least two RFEs [21].

Split Phase protocols, by contrast, can work with only one transceiver, but with a cost in terms of synchronization overhead [21].

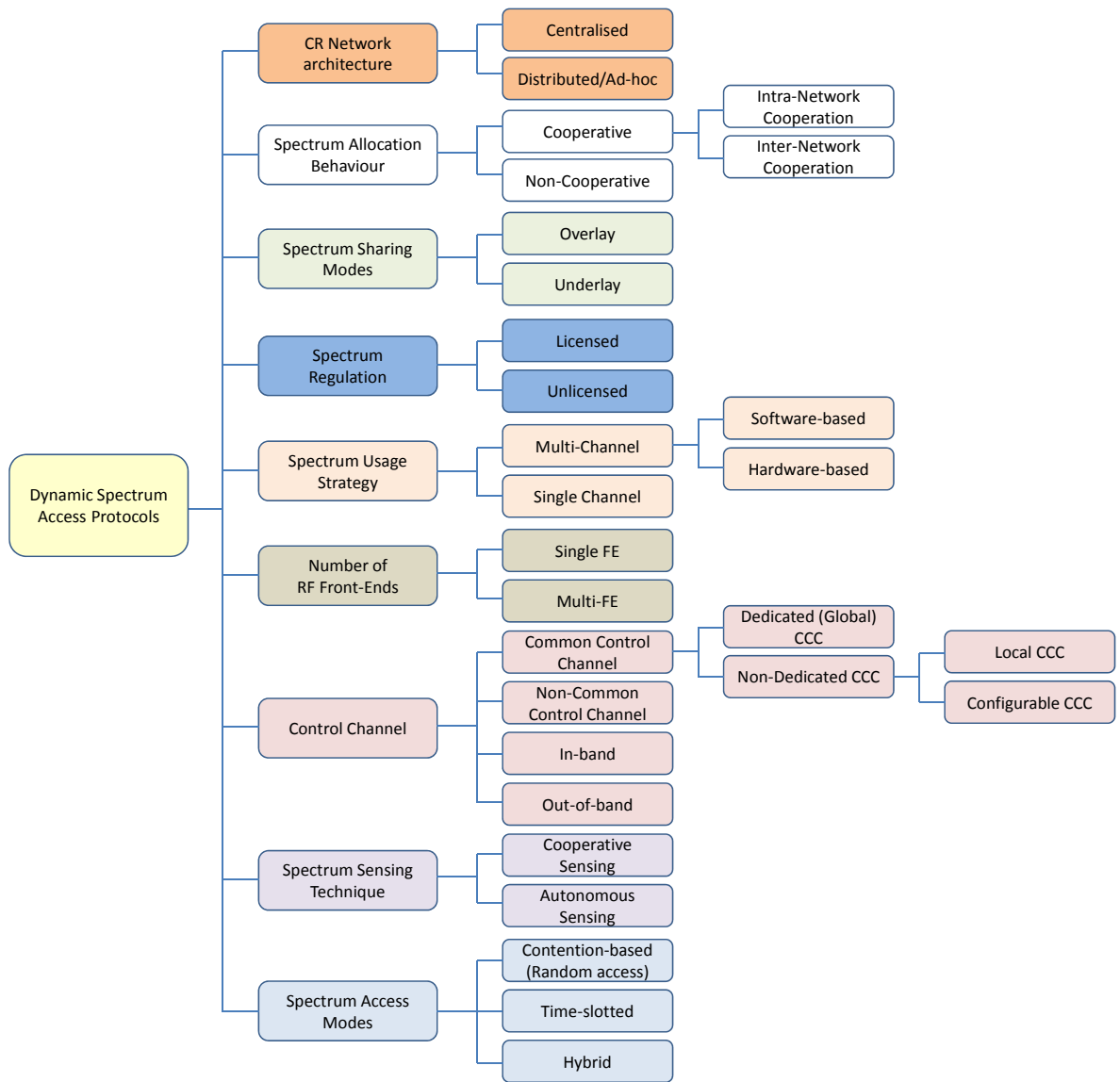A graphical representation of DSA protocol classes is given in Figure 7.

Figure 7: Classification of Dynamic Spectrum Access protocols (adapted from [22])

**Research status**

MAC protocols for spectrum sharing in cognitive radio systems have been extensively researched, and quite a large number of surveys and comparisons have been produced [9] [15] [19] [21] [24] [33] [37] [43] [44] [46] [47] [48] [49] [50] [51].

A general overview of the critical issues faced in CRN spectrum management is provided in [19]. In [21] a global CR MAC protocol classification is presented. Spectrum management issues and functionalities are discussed, and an overview of cognitive radio MAC algorithms implemented in DSA MAC protocols is given. Protocols are compared in terms of architecture, type of control channel, implementation of quiet periods, and need for synchronisation. Furthermore, protocols are categorised according to the following features: 1) complexity; 2) protocol architecture; 3) level of cooperation within the network; 4) management of signalling and data transfer during communication.

In [22], Ren et al. present a comprehensive overview and comparison of more than twenty different MAC protocols for distributed/ad-hoc cognitive wireless networks.

Comparisons of centralised and distributed CR MAC protocols are provided in [15] and [24]. In [24], centralized networks are further categorised depending on whether the controller takes part in data transmission among the secondary users. Otherwise, decentralized networks are classified according to how signalling and channel negotiation are managed into the network.

Bany Salameh and Krunz [36] present an overview of issues in protocol development for multi-hop CR networks, with a particular focus on transmission power control and power mask models.

In [37], CR MAC protocols are divided into four groups according to how control information is exchanged. A performance comparison for different control channel implementations is presented. The authors investigate PU channel scalability, the impact of PU activity, the amount of interference to the PU, and the impact of scanning (length/duration) and packet capture.

In [43], MAC functionalities and current research challenges of Cognitive Radio Ad Hoc Networks (CRAHNs) are discussed. Moreover, several CR MAC protocols are reviewed according to this classification. In [44], infrastructure-based and ad-hoc cognitive MAC protocols are classified according to the exploited medium access scheme and the number of exploited radio transceivers.

The main characteristics of several multi-channel MAC protocols are presented in [46], highlighting the additional functionalities that each multi-channel protocol should offer to operate in the OSA context. Furthermore, CR MAC protocols are classified by their mechanisms of channel negotiation/reservation. In [46] and [47], the authors discuss the main differences between classical multi-channel protocols and CR MAC protocols. Furthermore, [47] presents sensing policies and channel selection algorithms of certain CR MAC protocols. Comparisons of Multi-channel MAC protocols in terms of the number of transceivers, the need for synchronisation and the control channel implementation are provided in [9] and [31]. The performance in terms of throughput of several Multi-channel MAC protocols with different CC implementations is assessed in [48].

An overview of various aspects of Cognitive Radio including an extensive section on CR protocols is provided in [49]. While the authors focus on MAC protocols they also examine studies related to

network, transport, and application layer protocols and highlight certain aspects such as energy efficiency and QoS.

Control channel implementations are addressed in [33] and [50] . While Timalsina et al. [33] defines control channel categories for CR ad-hoc networks, Lo [50] classifies and compares various CCC concepts. He identifies control channel saturation, robustness to primary user activity, CCC coverage, and control channel security as primary challenges in CCC design.

In the course of this study, more than fifty spectrum sharing MAC protocols were identified. Most of the aforementioned surveys, however, cover only a few of those protocols (see Annex – List of Cognitive Radio MAC Protocols).

### *Research areas*

The majority of MAC protocols that were identified and surveyed in this study are designed for distributed/ad-hoc networks (80%), only 13% for centralized networks, and the rest for clustered networks.

Architectural aspects and self-organisation of CRN are addressed in a number of studies, some of which apply bio-inspired mechanisms and algorithms [52], swarm-intelligence algorithms [53] [54], stochastic algorithms [49] , graph theory [49], and game theory [55] [56] [57]. Improving the scalability of CR ad-hoc networks is the subject of [58] in which a scale-free topology is introduced that is robust to random attacks (node removal) and improves network performance.

Only few studies consider primary-secondary cooperation. In [59], a relay mechanism is presented that comprises a two-phase transmission of original and composite signals by PU and SU, respectively.

### Control Channel

The subject receiving the highest degree of attention is the development of robust control channel implementations. While the majority of current MAC protocols work with dedicated, common control channels, a number of studies present alternative approaches. A CCC-less solution which uses a dynamically alterable home channel on which control information and data are received is presented in [60].  In [61], control information is exchanged via an Adaptive Multiple Rendezvous Control Channel (AMRCC) using adaptive frequency hopping. In [62] , coordinated channel hopping algorithms for multi-user rendezvous are introduced. Pawelczak et al. [37] compare various CC concepts and find MRCC to perform best in terms of robustness and reliability. A hybrid approach combining a CCC with frequency hopping is presented in [63].

The Network Setup Problem (NSP), i.e. the initial identification of a suitable control channel without pre-determined CCC, is addressed in [64] [65] [66]. In [64], dedicated protocols are proposed for centralized and distributed CRNs while [66] addresses clustered networks. In [67], a mix of licensed and unlicensed channels plus backup channel is proposed.

A CPC-based centralised CR MAC protocol for multiple heterogeneous networks is presented in [39]. Energy efficiency is improved by distributing control using CPCs on multiple frequencies.

**Number of RF Front-Ends**

Reducing the number of RFEs whilst maintaining network performance is yet another focus area. The number of RFEs depends on the control channel implementation. A single-transceiver channel-hopping MAC protocol for hardware-constrained synchronous CRN is presented in [29].

According to [48], parallel-rendezvous protocols can perform better than single-rendezvous protocols with one RFE under a wide range of situations by eliminating the control channel bottleneck. DCC protocols, at the cost of two radios, outperform other protocols when there are many channels and when packets are long. Other protocols that use only one radio fail to perfectly monitor the channels and the status of the other nodes, thereby reducing the achievable throughput. However, when the number of channels is small, the performance cost of one dedicated channel is high [48].

**Cross-layer design**

Another major research topic is Cross-layer design. Kumar and Shin [68]  promote a combination of application awareness with channel-state knowledge to improve the QoS within a CRN. A cross-layer based multi-channel MAC protocol which integrates cooperative spectrum sensing at the PHY layer and overlay spectrum access at the MAC layer is proposed in [29]. A joint distributed power control, routing and MAC protocol for CRN is presented in [18]. The objective of this framework is to reduce energy consumption, while providing QoS (bit error rate, end-to-end delay, and throughput) for all nodes across the network. The authors find that cross-layer design has advantages for both high- and low-density networks. Energy efficiency is also the subject of [69] in which the author presents a TDMA based multi-channel MAC protocol that practises time and frequency domain negotiation to ensure collision free communication.

*Research projects*

Cognitive radio has been extensively researched in Europe, within the FP6 and FP7 frameworks (ACROPOLIS, ARAGORN, C2POWER, COGEU, CONSERN , CORE, COSSAR, CREW, CROWN, E2R, E3, EARTH, EULER, EUWB, FARAMIR, iCORE, OneFIT, PHYDYAS, ProSense, QoSMOS, QUASAR, S3ISE, SACRA, SAMURAI, SAPHYRE, SENDORA, WALTER), by other European research initiatives such as COST (TERRA, IC902, and IC1004), and in national research programs (C-PMSE, COGNAC, COMONSENS, CROPS2, EECRT, ENCOR, SPROACTIVE, TERROP, WISE).

All of these projects address the subject of spectrum sharing in one way or another. A few selected projects are listed below.

### ACROPOLIS (Advanced coexistence technologies for radio optimisation in licenced and unlicensed spectrum)

The main objective of the ACROPOLIS Network-of-Excellence (http://www.ict-acropolis.eu/) is to link experts and projects from around Europe working on coexistence technologies such as spectrum sharing and cognitive radio.

Acropolis addresses practically all aspects of CR, encompassing fundamental research methods, solution testing, regulation and standardisation, business aspects, and knowledge management. One of its goals is to complement the theoretical work that has been conducted on spectrum sharing, spectrum sensing, and spectrum management by means of experimental prototypes.

### CREW (Cognitive Radio Experimentation World)

Project CREW (www.crew-project.eu/) targets to establish an open federated test platform to facilitate experimentally-driven research on cognitive radio and cognitive networking strategies in view of horizontal and vertical spectrum sharing in licensed and unlicensed bands. CR MAC protocols and their sub-functionalities (such as spectrum sensing techniques, control channel implementations, etc.) can be tested and evaluated using the CREW infrastructure.

### CROWN (Cognitive Radio Oriented Wireless Networks)

The main purpose of the CROWN (www.fp7-crown.eu) project is to understand the technical issues of Cognitive Radios, through a proof of concept demonstrator. MAC layer protocol development is addressed in Work Package 5. One of its objectives is the development of techniques for spatially and spectrally aware CR transmission.

### OneFit (Opportunistic networks and Cognitive Management Systems for Efficient Application Provision in the Future InterneT)

OneFit (http://www.ict-onefit.eu/) aims to design, develop and validate the concept of opportunistic networks and respective cognitive management systems in the context of the Future Internet. The project's objectives include the development of control channels for the cooperation of cognitive management systems, and of algorithms for enabling opportunistic networks.

### S3ISE (Spectrum Sharing Systems for Improving Spectral Efficiency)

The main objective of S3ISE (http://cordis.europa.eu/projects/rcn/102595_en.html) is to develop an analytical cross layer framework for optimal radio resource modelling and allocation for multi secondary user spectrum sharing systems. In particular, the spectrum sensing function is to be

integrated into other upper layer functionalities such as power and rate control, and resource scheduling, which enables adaptive sensing.

### SaPHYRE (Sharing Physical Resources)

SAPHYRE (http://www.saphyre.eu) focuses on new principles and enabling technology for resource sharing in wireless networks, specifically for the sharing of spectrum and infrastructure for mobile communication services. The project intends to implement cross-layer design for resource sharing, including joint PHY/MAC design, and to develop a demonstrator testbed incorporating different scenarios and test cases.

### Future Research Topics

Following is a selection of recommendations for further research provided in the various studies and surveys that were evaluated for this report.

#### Spectrum sensing

- Develop better criteria for choosing probing channels in order to limit the overhead associated with spectrum sensing [21].
- Consider the impact of correlation to develop more efficient cooperative sensing schemes [21].
- Improve accuracy of models that account for false alarm and missed detection probabilities [44]
- Seamlessly integrate the information from multiple layers (e.g. sensing information from the PHY layer) in the working of the MAC protocol (cross-layer design) [22] [44], to enable and improve functions such as spectrum prediction [49] [22].

#### Control channel:

- Develop dynamic strategies to realize a reliable exchange of signalling information, and permit synchronization with neighbouring cognitive nodes [21].
- Develop concepts to provide effective distributed coordination between cognitive nodes in ad-hoc networks without relying on the existence of a pre-specified CCC [24] [36] [49].

#### CR network Performance/QoS

- Reduce packet loss and latency during channel handovers, for instance through the use of backup channels [21] [49] [22].
- Enable guaranteed service quality for secondary networks [36] [49].
- Establish QoS in ad-hoc CR networks without a global CC.
- Devise protocols that adapt CR transmissions based on the PU traffic pattern [44].
- Investigate distributed collision avoidance mechanisms [22].
- Implement dynamic adaptation of the spectrum sharing mode (overlay/underlay) to improve network performance [22].

#### Network Coordination and Coexistence

- Investigate coordination and coexistence between multiple heterogeneous DSA networks [24].
- Extend the scope of CR research beyond opportunistic ad-hoc networks to cellular networks, for instance to realize the coexistence of femtocells and macrocells [21].
- Address the dynamic radio range issue, i.e., the variation of the number of neighbouring cognitive nodes with channel frequency.

#### Radio resource management

- Utilise advances in DSA algorithm design for integration into CR MAC protocols [21].

#### Primary User protection

- Limit interference to PUs through dynamic neighbourhood- dependent power masks [36].

#### Test and evaluation

- Develop performance metrics that capture CR-specific characteristics to evaluate different MAC protocols [44].
- Intensify experimental validation of CR concepts and proposals [49].

**Test and verification**

Most of the MAC protocols studied in this report have been evaluated through simulations, only; there is very little experimental verification work in this field. Although numerous CR testbeds have been developed during the past years [70] [71] [72] [73] [74] [75] [76] most of these are small-scale installations, featuring a few nodes at best.

The CREW (Cognitive Radio Experimentation World) project developed a federation of testbeds [75] which allows evaluating CR functions with different wireless technologies, such as LTE, 802.11 WLAN, or 802.15.4 WPAN.

Jia and Zhang [77] proposed an experimental modular platform to evaluate the performance of the different elements of a CR system (Figure 8).
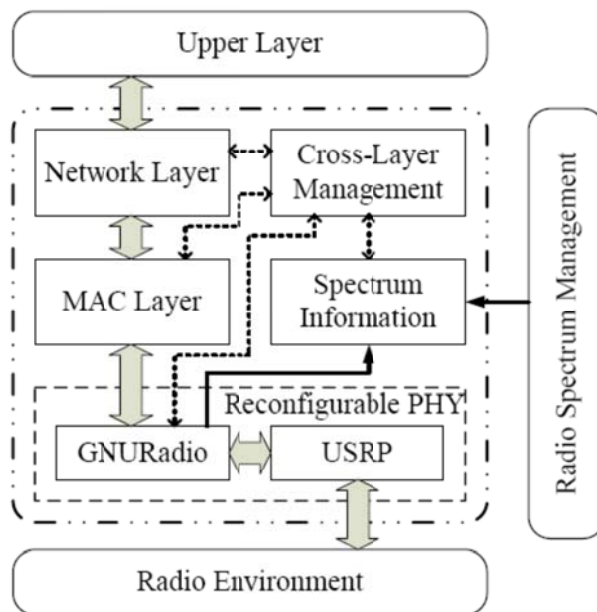
Figure 8: Cognitive Radio systems Testbed architecture [77]

CR testbed suitable to analyse cross-layer functions, i.e., spanning the physical, MAC, and Application layers are presented in [78] and [79], with the latter study focusing on mesh sensor networks. Xu et al. [80] present a test platform for heterogeneous wireless networks utilising the CPC concept.

## Technology readiness

### Standardisation

Spectrum sharing mechanisms have been included in a number of wireless standards, for instance in IEEE 802.11 (WLAN), Bluetooth, and ECMA-392 (UWB). More recently, adaptive sharing mechanisms such as DAA have been included in ETSI specifications for UWB [81] and RFID [82]. CR mechanisms have been specified in the IEEE 802.22 WRAN standard [83]. The IEEE 802.11af Task Group is currently developing MAC and PHY specifications for WLAN operating in TVWS.

In Europe, the Technical Committee for Reconfigurable Radio Systems (TC RRS) of ETSI is working on the standardisation of Cognitive Radio. TC RRS addresses various aspects of CR (shared and dedicated spectrum use, licensed and unlicensed), with a focus on TVWS applications [84]. As far as spectrum sharing protocols are concerned, TC RRS adopted the aforementioned CPC concept. The final implementation, however, has not yet been defined because, as stated in [42] "none of the options is by itself suitable for enabling a full implementation of the Cognitive Control Channel. Therefore, it is expected that the final Cognitive Control Channel implementation will be based on a combination of different radio-independent and radio-dependent solutions". In addition ETSI notes that further experimentation work is essential to obtain better insight on Cognitive Control Channel implementation issues.

### Field trials and deployments

While there are a few examples for static spectrum sharing, such as Advanced Wireless Services (AWS) in the USA, the only deployment of DSA to date is for TVWS applications based on geolocation databases [85]. So far, however, commercial deployment of TV white spaces in the US has been extremely limited, partly because the available spectrum varies by market, and in the more highly populated areas, there are fewer broadcast channels with white spaces for unlicensed use [85].

In Europe, a 10-month field test of TVWS technology, the Cambridge White Space Trials, which involved 17 companies, was held in 2011-2012 [86]. UK regulator Ofcom has begun the development of a Voluntary National Specification (VNS) that lays out the rules and requirements for devices using UHF TV Band White Spaces [87].

## Summary and Conclusion – Implications for Radio Spectrum Policy

Although significant research efforts have been made during the past ten years the development and implementation of technology-neutral spectrum sharing protocols is still in an early stage. There are still many issues to be solved in the technical, commercial, and regulatory domains which are, to complicate matters, closely interrelated.

The majority of studies address mobile cognitive radio ad-hoc networks, and dozens of different protocols have been proposed. There is, however, no clear direction or tendency, although some promising concepts exist. One of the main challenges in this area is to develop a robust control and coordination channel that enables an exchange of information between cognitive nodes.

Current standardisation work, in contrast, focuses on a centralised approach to enable the coexistence of heterogeneous networks, in particular for geolocation-based TVWS applications that rely on a common Cognitive Pilot Channel. Even in this case, however, there has been no agreement on the protocol and control channel implementation.

Besides the development of a suitable control channel scheme various research challenges remain, such as cross-layer design, and support for and integration of cooperative spectrum sensing. Furthermore, it will be necessary to conduct more realistic simulations and verifications, for instance of the behaviour and performance of MAC protocols in scenarios with multiple heterogeneous secondary and primary networks. Experimental verification of is of major importance in this context. Numerous testbeds exist but common rules and performance metrics to evaluate CR protocol and system performance still have to be defined. Considering that so far no fundamental technical limitations have been identified it can be assumed that the current technical shortcomings will be solved during the next years.

While MAC layer protocols are fundamental to dynamic spectrum sharing they constitute only a small part of the CR system. Given the complexity of the subject and the many degrees of freedom, it is unlikely that there will be one solution for dynamic spectrum sharing that suits all applications and technologies. Likewise, the amount of spectrum that can effectively be gained through spectrum sharing will vary, depending on the application and technology.

The big challenges therefore lie in the regulatory and commercial domains. Regulation will have to motivate and guide spectrum users in order to encourage the adoption and deployment of spectrum sharing solutions.

## Annex – List of Cognitive Radio MAC Protocols

| Protocol name | Protocol Acronym | Architecture | Year of publication |
|---|---|---|---|
| Aaptive Medium Access Control | AMAC | Distributed | 2009 |
| Ad hoc SEC MAC protocol | AS-MAC | Distributed | 2006 |
| Cognitive MAC | C-MAC | Distributed | 2007 |
| Coordinated Bandwidth Sharing-MAC | CBS-MAC | Centralised | 2008 |
| CPC on Different Frequencies (-MAC) | CPCDF-MAC | Centralised | 2010 |
| Distributed Cognitive  MAC | COMAC | Distributed | 2009 |
| Cognitive Radio Carrier Sense Multiple Access | CR-CSMA | Distributed | 2010 |
| Cognitive Radio-EnAbled Multi-channel MAC | CREAM-MAC | Distributed | 2008 |
| Carrier Sense Multiple Access MAC | CSMA-MAC | Centralised | 2007 |
| Dynamic Channel Assignment MAC | DCA-MAC | Distributed | 2000 |
| Decentralized Cognitive MAC | DC-MAC | Distributed | 2007 |
| Distributed Cognitive Radio MAC | DCR-MAC | Distributed | 2009 |
| Distributed Coordinated Spectrum Sharing MAC protocol | DCSS-MAC | Distributed | 2007 |
| Distance-Dependent MAC | DD-MAC | Distributed | 2010 |
| Distributed Frequency Agile-MAC | DFA-MAC | Distributed | 2008 |
| Dynamic Hopping MAC | DH-MAC | Distributed | 2010 |
| Dynamic Intelligent Management of Spectrum for Ubiquitous Mobile-access Network | DIMSUMNet | Centralised | 2005 |
| Dynamic Open Spectrum Sharing protocol | DOSS | Distributed | 2005 |
| Dynamic Spectrum Access MAC | DSA-driven MAC | Centralised | 2008 |
| Dynamic Spectrum Access Protocol | DSAP | Centralised | 2005 |
| Dual Unlicensed Band MAC | DUB-MAC | Distributed | 2007 |
| Energy-efficient Cognitive Radio multichannel MAC | ECR-MAC | Distributed | 2010 |
| Efficient Dynamic Adjusting MAC | EDA-MAC | Distributed | 2010 |
| Evolutionary opportunistic Spectrum Access protocol | ESA | Distributed | 2010 |
| Hardware-constrained MAC protocol | HC-MAC | Distributed | 2008 |
| Heterogeneous Distributed MAC protocol | HD-MAC | Distributed | 2005 |
| Hybrid Multi-Channel MAC Protocol | HMCMP | Distributed | 2006 |
| IEEE 802.22 | IEEE 802.22 | Centralised | 2010 |
| Integer Linear Programming (ILP)-based MAC | ILP-based MAC | Distributed | 2006 |
| Parallel Rendezvous Multi-Channel MAC | McMAC | Distributed | 2007 |
| Multi-Channel MAC | MC-MAC | Centralised | 2011 |
| Multi-channel Cognitive Radio MAC | MCR-MAC | Distributed | 2009 |
| Distributed Multi-channel MAC | MMAC-CR | Distributed | 2010 |
| Cross-Layer Based Opportunistic MAC | O-MAC/CLBO-MAC | Distributed | 2008 |
| Opportunistic Cognitive MAC | OC-MAC | Distributed | 2008 |
| Opportunistic Periodic MAC | OP-MAC | Distributed | 2010 |
| Opportunistic Spectrum Medium Access Control | OS-MAC | Clustered | 2008 |

| Opportunistic Spectrum Access MAC | OSA-MAC | Distributed | 2008 |
|---|---|---|---|
| Primary Channel Assignment Based MAC | PCAM | Distributed | 2004 |
| Price-based MAC | P-MAC | Distributed | 2008 |
| Polarization-based Long-Range Communication Directional MAC | PLRC-DMAC | Distributed | 2011 |
| Statistical Channel Allocation MAC | SCA-MAC | Distributed | 2007 |
| Stochastic Medium Access | SMA | Distributed | 2011 |
| Self-scheduling Multi-Channel cognitive MAC | SMC-MAC | Distributed | 2011 |
| Single-Radio Adaptive Channel | SRAC | Distributed | 2007 |
| Spectrum access WITh backup Channel | SWITCH | Distributed | 2012 |
| Synchronized MAC | SYN-MAC | Distributed | 2008 |
| Throughput-aimed MAC | T-MAC | Distributed | 2010 |
| A Full Duplex Multi-channel MAC | - | Distributed | 2006 |

Figure 9: CR MAC protocols investigated in this report

| Protocol acronym | Protocol name | Survey reference |
|---|---|---|
| C-MAC | Cognitive MAC | [15] [21] [22] [24] [37] [44] [50] [88] [89] [90] |
| CREAM-MAC | Cognitive Radio-enabled multi-channel MAC | [22] [50] [31] |
| DOSS | Dynamic Open Spectrum Sharing protocol | [14] [15] [21] [22] [24] [33] [37] [44] [47] [50]  [88] [89] [90] |
| HC-MAC | Hardware-constrained MAC | [15] [21] [22] [24] [31] [33] [44] [47] [50]  [88] [89] [90] |
| MC-MAC | Multi-Channel MAC | [22] |
| OS-MAC | Opportunistic Spectrum MAC | [15] [21] [31] [33] [37] [44] [47] [50] [88] |
| SRAC | Single-Radio Adaptive Channel | [15] [22] [24] [31] [33] [37] [44] [50] [88] [89]  [90] |
| SYN-MAC | Synchronized MAC | [21] [22] [33] [44] [50] [88] |

Table 3: MAC protocol coverage in surveys (selected examples)

## List of Figures

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# Bibliography

[1]  European Commission, "eCommunications: Radio Spectrum Policy: Radio Spectrum Policy Programme | Europa - Information Societys," [Online]. Available: http://ec.europa.eu/information_society/policy/ecomm/radio_spectrum/rspp/index_en.htm#concrete_actions. [Accessed 20 September 2012].

[2]  Radio Spectrum Policy Group (RSPG), "Report on Collective Use of Spectrum (CUS) and other spectrum sharing approaches," November2011.

[3]  European Commission, "eCommunications: Radio Spectrum Policy: Radio Spectrum Policy Group | Europa - Information Society," [Online]. Available: http://ec.europa.eu/information_society/policy/ecomm/radio_spectrum/eu_policy/rspg/index_en.htm. [Accessed 20 September 2012].

[4]  ITU-R, *General principles and methods for sharing between radiocommunication services or between radio stations,* ITU-R, 2001.

[5]  BEREC/RSPG, "Joint BEREC/RSPG Report on Infrastructure and spectrum sharing in mobile/wireless networks," Radio Spectrum Policy Group, 16 June 2011.

[6]  Q. Zhao and A. Swami, *A Survey of Dynamic Spectrum Access: SP & Networking Perspectives,* Honolulu, 2007.

[7]  J. M. Peha, "Sharing Spectrum through Spectrum Policy Reform and Cognitive Radio," 1-1-2008.

[8]  R. Menon, "Interference Avoidance based Underlay Techniques for Dynamic Spectrum Sharing," April 30, 2007.

[9]  V. D. Chakravarthy, "Evaluation of Overlay/Underlay Waveform via SD-SMSE Framework for Enhancing Spectrum Efficiency," Wright State University, 2008.

[10] X. Jing, "Spectrum Coordination Protocols and Algorithms for Cognitive Radio Networks," January, 2008.

[11] M. Denkovska, P. Latkoski and L. Gavrilovska, "Geolocation database approach for secondary spectrum usage of TVWS," in *Telecommunications Forum (TELFOR), 2011 19th*, 22-24 Nov. 2011.

[12] L. Q. Jan Kruys, Sharing RF Spectrum with Commodity Wireless Technologies, Springer, 2011.

[13] L. Hester and A. D. Ridley, "Cognitive Radio Networks: Not Your Father's Wireless Network," *THE TELECOMMUNICATIONS REVIEW 2008,* pp. 44-54, 2008.

[14] C. Liu, "Spectrum Sharing In Dynamic Spectrum Access Networks," Philadelphia, PA 19104, June 22, 2009.

[15] Y.-C. Liang, K.-C. Chen, G. Li and P. Mahonen, "Cognitive Radio Networking and Communications: An Overview," *Vehicular Technology, IEEE Transactions on,* vol. 60, no. 7, pp. 3386-3407, Sept. 2011.

[16] K. R. C. W. K. A. K. L. B. Marco Di Felice, "End-to-end protocols for Cognitive Radio Ad Hoc Networks: An evaluation study," *Performance Evaluation,* vol. 68, no. 9, pp. 859-875, September 2011.

[17] S. Das, J. Malyar and D. Joslyn, "Device to Database Protocol for White Space, draft-das-paws-protocol-02," IETF, 14 07 2012. [Online]. Available: http://datatracker.ietf.org/doc/draft-das-paws-protocol/?include_text=1. [Accessed 10 October 2012].

[18] N. Nie, K. Jaffres-Runser and C. Comaniciu, "On the Trade-offs of Cross-Layer Protocols for Cognitive Radio Networks," in *Cognitive Radio Networks*, Y. Xiao and F. Hu, Eds., Auerbach Publications, CRC Press, Taylor & Francis Group.

[19] I. Akyildiz, W.-Y. Lee, M. Vuran and S. Mohanty, "A survey on spectrum management in cognitive radio networks," *Communications Magazine, IEEE,* vol. 46, no. 4, pp. 40-48, April 2008.

[20] P.-Y. Huang, "Cognitive Media Access Control," in *Advances in Cognitive Radio Systems*, C. Wang and J. M. III, Eds., InTech, 2012, pp. 43-64.

[21] A. De Domenico, E. Strinati and M.-G. Di Benedetto, "A Survey on MAC Strategies for Cognitive Radio Networks," *Communications Surveys & Tutorials, IEEE,* vol. 14, no. 1, pp. 21-44, First Quarter 2012.

[22] P. Ren, Y. Wang, Q. Du and J. Xu, "A survey on dynamic spectrum access protocols for distributed cognitive wireless networks," *EURASIP Journal on Wireless Communications and Networking,* vol. 2012:60, 2012.

[23] V. S. Rao, "Allocation of Opportunistic Spectrum for Cognitive Radio Ad hoc Networks," Delft University of Technology, Delft, The Netherlands, Oct. 2009.

[24] T. V. Krishna and A. Das, "A survey on MAC protocols in OSA networks," *Computer Networks,* vol. 53, p. 1377–1394, 2009.

[25] D. a. A. F. Gözüpek, "An Opportunistic Pervasive Networking Paradigm: Multi-Hop Cognitive Radio Networks," in *Pervasive Computing and Networking*, M. S. Obaidat, M. Denko and I. Woungang, Eds., Chichester, UK, John Wiley & Sons, 2011.

[26] L. Hu, V. B. Iversen and L. Dittmann, "Survey of PHY and LINK Layer Functions of Cognitive Radio Networks for Opportunistic Spectrum Sharing," in *Communications and Networking in China*, P. Bond, Ed., Springer Berlin Heidelberg, 2009.

[27] M. G. Khoshkholgh, K. Navaie and H. Yanikomeroglu, "Access Strategies for Spectrum Sharing in Fading Environment: Overlay, Underlay, and Mixed," *IEEE TRANSACTIONS ON MOBILE COMPUTING,* vol. 9, no. 12, pp. 1780-1793, 2010.

[28] H.Feizresan and M. J. Omidi, "Spectrum Sharing in Cognitive Radio Networks," 2009.

[29] H. Su, "Design and Analysis of Opportunistic Mac Protocols for Cognitive Radio Wireless Networks," December 2010.

[30] M. Song, C. Xin, Y. Zhao and X. Cheng, "Dynamic spectrum access: From cognitive radio to network radio," *Wireless Communications, IEEE,* vol. 19, no. 1, pp. 23-29, February 2012.

[31] R. S. d. Castro, P. Godlewski and P. Martins, "An Overview of DSA via Multi-Channel MAC Protocols," *Advances in Vehicular Networking Technologies,* 2011.

[32] D. Čabrić, S. M. Mishra, D. Willkomm, R. Brodersen and A. Wolisz, "A Cognitive Radio Approach for Usage of Virtual Unlicensed Spectrum," in *14th IST Mobile Wireless Communications Summit 2005*, 2005.

[33] S. K. Timalsina, S. Moh and I. Chung, "A Taxonomy and Review of MAC Protocols in Cognitive Radio Ad Hoc Networks," in *4th International Conference on Wireless Information Networks & Business Information System (WINBIS 2012)* , Feb 27 – 28, 2012.

[34] Y. R. Kondareddy, "MAC and Routing Protocols for Multi-Hop Cognitive Radio Networks," August 9, 2008.

[35] K. Bian, J.-M. ". Park and R. Chen, "A Quorum-based Framework for Establishing Control Channels in Dynamic Spectrum Access Networks via-multi-channel-mac-protocols," in *MobiCom '09, Proceedings of the 15th annual international conference on Mobile computing and networking*, Beijing, China, September 20–25, 2009.

[36] H. Bany Salameh and M. Krunz, "Channel access protocols for multihop opportunistic networks: challenges and recent developments," *IEEE Network,* vol. 23, no. 4, pp. 14-19, July-August 2009.

[37] P. Pawelczak, S. Pollin, H.-S. So, A. Bahai, R. Prasad and R. Hekmat, "Performance Analysis of Multichannel Medium Access Control Algorithms for Opportunistic Spectrum Access," *Vehicular Technology, IEEE Transactions on,* vol. 58, no. 6, pp. 3014-3031, July 2009.

[38] "E2RII 2 Whitepaper: "The E2RII Flexible Spectrum Management (FSM) Framework and Cognitive Pilot Channel (CPC) Concept - Technical and Business Analysis and Recommendations"," FP6 Project E2RII, November 2007.

[39] N. Bolívar and J. L. Marzo, "Distributed Control and Signaling using Cognitive Pilot Channels in a Centralized Cognitive Radio Network," *International Journal on Advances in Telecommunications,* vol. 3, no. 3&4, pp. 263-270, 2010.

[40] ETSI, "ETSI TR 102 683 V1.1.1 (2009-09) Reconfigurable Radio Systems (RRS); Cognitive Pilot Channel (CPC)," ETSI, September 2009.

[41] ETSI, "ETSI TR 102 684 V1.1.1 (2012-04); Reconfigurable Radio Systems (RRS); Feasibility Study on Control Channels for Cognitive Radio Systems," ETSI, April 2012.

[42] V. Stavroulaki, K. Tsagkaris, P. Demestichas, J. Gebert, M. Mueck, A. Schmidt, R. Ferrus, O. Sallent, M. Filo, C. Mouton and L. Rakotoharison, "Cognitive control channels: from concept to identification of implementation options," *Communications Magazine, IEEE,* vol. 50, no. 7, pp. 96-108, July 2012.

[43] W. Y. L. a. K. R. C. I. F. Akyildiz, "CRAHNs: Cognitive Radio Ad Hoc Networks," *Ad Hoc Networks,* vol. 7, no. 5, p. 810–836, July 2009.

[44] C. Cormio and K. R. Chowdhury, "A survey on MAC protocols for cognitive radio networks," *Ad Hoc Networks,* pp. 1315-1329, 03 February 2009.

[45] X. Z. a. H. Su, "CREAM-MAC: Cognitive Radio-Enabled Multi-channel MAC forWireless Networks," in *Cognitive Radio Mobile Ad Hoc Networks*, F. R. Yu, Ed., Springer, 2011, pp. 129-158.

[46] A. K. L. Yau, P. Komisarczuk and a. P. D. Teal, "On Multi-Channel MAC Protocols in Cognitive Radio Networks," in *Telecommunication Networks and Applications Conference ATNAC 2008. Australasian,*, December 2008.

[47] H. Wang, H. Qin and L. Zhu, "A Survey on MAC Protocols for Opportunistic Spectrum Access in Cognitive Radio Networks," in *Computer Science and Software Engineering, 2008 International Conference on*, 12-14 Dec. 2008.

[48] J. Mo, H.-S. So and J. Walrand, "Comparison of Multichannel MAC Protocols," *Mobile Computing, IEEE Transactions on ,* vol. 7, no. 1, pp. 50-65, Jan. 2008.

[49] J. Marinho and E. Monteiro, "Cognitive radio: survey on communication protocols, spectrum decision issues, and future research directions," *Wireless Networks,* pp. 147-164, 2012.

[50] B. F. Lo, "A survey of common control channel design in cognitive radio networks," *Physical Communication,* vol. 4, pp. 26-39, 2011.

[51] V. Katarwar and A.V.Kulkarni, "A survey on spectrum management framework in cognitive radio networks– research challenges and future goals," *World Journal of Science and Technology,* vol. 2, no. 3, pp. 144-150, 2012.

[52] B. Atakan, B. Gulbahar and O. B. Akan, "Immune system-inspired evolutionary opportunistic spectrum access in cognitive radio ad hoc networks," in *Ad Hoc Networking Workshop (Med-Hoc-Net), 2010 The 9th IFIP Annual Mediterranean*, 23-25 June 2010.

[53] P. Hu and M. Ibnkahla, "A Consensus-based Protocol for Spectrum Sharing Fairness in Cognitive Radio Ad Hoc & Sensor Networks," in *IEEE International Conference on Communications 2012 (ICC 2012)*, 2012.

[54] T. Renk, C. Kloeck, D. Burgkhardt, F. K. Jondral, D. Grandblaise, S. Gault and J. C. Dunat, "Bio-Inspired Algorithms for Dynamic Resource Allocation in Cognitive Wireless Networks," in *Cognitive Radio Oriented Wireless Networks and Communications, 2007. CrownCom 2007. 2nd International Conference on ,*, 1-3 Aug. 2007.

[55] M. Liu and Y. Wu, "Spectum Sharing as Congestion Games," in *Communication, Control, and Computing, 2008 46th Annual Allerton Conference on*, 23-26 Sept. 2008.

[56] B. Wang, Y. Wu and K. R. Liu, "Game theory for cognitive radio networks: An overview," *Computer Networks,* p. 2537–2561, 2010.

[57] R. Southwell, J. Huang and X. Liu, "Spectrum mobility games," in *INFOCOM, 2012 Proceedings IEEE*, 25-30 March 2012.

[58] A. Rajaee, M. Saedy and A. Sahebalam, "Competitive spectrum sharing for cognitive radio on Scale-Free wireless networks," in *Wireless Communications and Mobile Computing Conference (IWCMC), 2011 7th International*, 4-8 July 2011.

[59] Y. Han, A. Pandharipande and S. Ting, "Cooperative spectrum sharing via controlled amplify-and-forward relaying," in *Personal, Indoor and Mobile Radio Communications, 2008. PIMRC 2008. IEEE 19th International Symposium on*, 15-18 Sept. 2008.

[60] C. Xin and X. Cao, "A Cognitive Radio Network Architecture without Control Channel," in *Global Telecommunications Conference, 2009. GLOBECOM 2009. IEEE*, Nov. 30 2009-Dec. 4 2009.

[61] C. Cormio and K. R. Chowdhury, "Common control channel design for cognitive radio wireless ad hoc networks using adaptive frequency hopping," *Ad Hoc Networks,* no. 8, p. 430–438, 2010.

[62] R. Gandhi, C.-C. Wang and Y. Hu, "Fast Rendezvous for Multiple Clients for Cognitive Radios Using Coordinated Channel Hopping," in *The 9th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON), 2012*, Seoul, Korea, June 18 – 21, 2012.

[63] Z. Htike, J. Lee and C. S. Hong, "A MAC protocol for cognitive radio networks with reliable control channels assignment," in *Information Networking (ICOIN), 2012 International Conference on*, 1-3 Feb. 2012.

[64] Y. Kondareddy, P. Agrawal and K. Sivalingam, "Cognitive Radio Network setup without a Common Control Channel," in *Military Communications Conference, 2008. MILCOM 2008. IEEE*, 16-19 Nov. 2008.

[65] S. W. Kim and B.-S. Kim, "An Efficient MAC Protocol for Improving the Network Throughput for Cognitive Radio Networks," in *Next Generation Mobile Applications, Services and Technologies, 2009. NGMAST '09. Third International Conference on*, 15-18 Sept. 2009.

[66] S. Liu, L. Lazos and M. Krunz, "Cluster-Based Control Channel Allocation in Opportunistic Cognitive Radio Networks," *Mobile Computing, IEEE Transactions on,* vol. 11, no. 10, pp. 1436-1449, Oct. 2012.

[67] M. A. Kalil, A. Puschmann and A. Mitschele-Thiel, "SWITCH: A Multichannel MAC Protocol for Cognitive Radio Ad Hoc Networks," in *2012 IEEE 76th Vehicular Technology Conference, VTC2012-Fall*, 3-6 September 2012.

[68] A. Kumar and K. G. Shin, "Application-aware dynamic spectrum access," *Wireless Networks,* vol. 18, no. 3, pp. 257-275, April 2012.

[69] S. M. Kamruzzaman, "An Energy Efficient Multichannel MAC Protocol for Cognitive Radio Ad Hoc Networks," *International Journal of Communication Networks and Information Security (IJCNIS),* vol. 2, no. 2, pp. 112-119, August 2010.

[70] O. Gustafsson, K. Amiri, D. Andersson, A. Blad, C. Bonnet, J. Cavallaro, J. Declerck, A. Dejonghe, P. Eliardsson, M. Glasse, A. Hayar, L. Hollevoet, C. Hunter, M. Joshi, F. Kaltenberger, R. Knopp, K. Le, Z. Miljanic, P. Murphy and Naesse, "Architectures for cognitive radio testbeds and demonstrators — An overview," in *Cognitive Radio Oriented Wireless Networks & Communications (CROWNCOM), 2010 Proceedings of the Fifth International Conference on*, 9-11 June 2010.

[71] A. Khattab, D. Perkins and M. Bayoumi, "Experimental evaluation of Opportunistic Spectrum Access in distributed cognitive radio networks," in *Wireless Communications and Mobile Computing Conference (IWCMC), 2012 8th International* , 27-31 Aug. 2012.

[72] P. Sutton, J. Lotze, H. Lahlou, B. Ozgul, S. Fahmy, K. Nolan, J. Noguera and L. Doyle, "Multi-platform demonstrations using the Iris architecture for cognitive radio network testbeds," in *Cognitive Radio Oriented Wireless Networks & Communications (CROWNCOM), 2010 Proceedings of the Fifth International Conference on*, 9-11 June 2010.

[73] M. Dardaillon, K. Marquet, T. Risset and A. Scherrer, "Software defined radio architecture survey for cognitive testbeds," in *Wireless Communications and Mobile Computing Conference (IWCMC), 2012 8th International*, 27-31 Aug. 2012.

[74] T. L. Y. T. Q. X. W. P. Zhaojun He, "The UESTC reconfigurable Cognitive radio testbed," in *6th International ICST Conference on Communications and Networking in China 2011 (Chinacom 2011)*, 2011.

[75] FP7 Project CREW, "CREW testbed | CREW project," [Online]. Available: http://www.crew-project.eu/crewtestbed.

[76] Z. Chen, C. Zhang, F. Lin, J. Yu, X. Li, Y. Song, R. Ranganathan, N. Guo and R. Qiu, "Towards a large-scale cognitive radio network: Testbed, intensive computing, frequency agility and security," in *Computing, Networking and Communications (ICNC), 2012 International Conference on* , 2012-Feb. 2 2012.

[77] J. Jia and Q. Zhang, "A Testbed Development Framework for Cognitive Radio Networks," in *Communications, 2009. ICC '09. IEEE International Conference on* , 14-18 June 2009.

[78] E. Rodriguez-Colina, V. Ramos-R and G. Laguna-Sanchez, "Cross layer analysis for a dynamic spectrum allocation system," in *Engineering Applications (WEA), 2012 Workshop on*, 2-4 May 2012.

[79] C. Edmonds, D. Joiner, S. Springer, K. Stephen and B. Hamdaoui, "Cognitive Wireless Mesh Network Testbed," in *Wireless Communications and Mobile Computing Conference, 2008. IWCMC '08. International*, 6-8 Aug. 2008.

[80] Y. Xu, Z. Feng and P. Zhang, "Research on Cognitive Wireless Networks: Theory, Key Technologies and testbed," in *Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), 2011 Sixth International ICST Conference on*, 1-3 June 2011.

[81] ETSI, "ETSI TS 102 754 V1.2.2 (2011-02); Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD); Technical characteristics of Detect-And-Avoid (DAA) mitigation techniques for SRD equipment using Ultra Wideband (UWB) technology," ETSI, 2011.

[82] ETSI, "ETSI TS 102 902 V1.2.1rev15 (2012-09); Electromagnetic compatibility and radio spectrum matters (ERM); Methods, parameters and test procedures for cognitive interference mitigation towards ER-GSM for use by UHF RFID using Detect-And-Avoid (DAA) or other s," ETSI, 2012.

[83] IEEE Standards Association, *Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and Procedures for Operation in the TV Bands,* IEEE Computer Society, 2011.

[84] M. Mueck, *ETSI TC RRS (Reconfigurable Radio Systems) - Actual state of CR/SDR standardisation work,* 2012.

[85] Rysavy Research, LLC, "Spectrum Sharing - The Promise and The Reality," Rysavy Research, LLC, July 2012.

[86] Cambridge White Spaces Consortium, "Recommendations for Implementing the Use of White Spaces: Conclusions from the Cambridge TV White Spaces Trial," Cambridge White Spaces Consortium, 2012.

[87] InterDigital, "Dynamic Spectrum Management," InterDigital, October 2012.

[88] U. S. Khan and T. Maqsood, "CRN Survey and A Simple Sequential MAC Protocol for CRN Learning," in *COCORA 2012 : The Second International Conference on Advances in Cognitive Radio*, 2012.

[89] P. Pawelczak, S. Pollin, H.-S. W. So, A. Bahai, R. V. Prasad and R. Hekmat, "Quality of Service Assessment of Opportunistic Spectrum Access: A Medium Access Control Approach," *IEEE Wireless Communications,* pp. 20-29, October 2008.

[90] P. Pawelczak, S. Pollin, H.-S. So, A. Motamedi, A. Bahai, R. Prasad and R. Hekmat, "State of the Art in Opportunistic Spectrum Access Medium Access Control Design," in *Cognitive Radio Oriented Wireless Networks*

*and Communications, 2008. CrownCom 2008. 3rd International Conference on*, 15-17 May 2008.

[91] A. Mishra and S. Sankaranarayanan, "WLC25-5: A Multi-channel MAC Protocol for Dynamic Spectrum Sharing Primary Secondary Systems," in *IEEE Global Telecommunications Conference, 2006. GLOBECOM '06*, Nov. 27 2006-Dec. 1 2006.

[92] J. Park and M. v. d. Schaar, "Cognitive MAC Protocols Using Memory for Distributed Spectrum Sharing Under Limited Spectrum Sensing," *IEEE TRANSACTIONS ON COMMUNICATIONS,* vol. 59, no. 9, pp. 2627-2637, September 2011.

[93] SDR Forum, "Working Document Towards a Preliminary Draft New Report on Cognitive Radio in Land Mobile Service," SDR Forum, 24 JANUARY 2008.

[94] L. Ma, X. Han and C.-C. Shen, "Dynamic open spectrum sharing MAC protocol for wireless ad hoc networks," in *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, 8-11 Nov. 2005.

[95] T. Chen, M. Matinmikko and H. Zhang, "A Novel Control Channel Management in CogMesh Networks," in *Vehicular Technology Conference (VTC Fall), 2011 IEEE*, 5-8 Sept. 2011.

[96] T. Chen, H. Zhang, M. Katz and Z. Zhou, "Swarm Intelligence Based Dynamic Control Channel Assignment in Cogmesh," in *Communications Workshops, 2008. ICC Workshops '08. IEEE International Conference on*, 19-23 May 2008.

[97] N. D. Grace, "FCC CHAIRMAN JULIUS GENACHOWSKI ANNOUNCES PLANS TO INITIATE FORMAL STEPS ON SPECTRUM RECOMMENDATIONS FROM THE PRESIDENT'S COUNCIL OF ADVISORS ON SCIENCE AND TECHNOLOGY (PCAST) -," FierceWireless, 13 September 2012. [Online]. Available: http://www.fiercebroadbandwireless.com/story/35-ghz-spectrum-sharing-effort-could-take-years-produce-results/2012-09-16.

[98] President's Council of Advisors on Science and Technology, "Realizing The Full Potential Of Government-Held Spectrum To Spur Economic Growth," 2012.

[99] T. Parker, "3.5 GHz spectrum sharing effort could take years to produce results," FierceBroadbandWireless, 16 September 2012. [Online]. Available: http://www.fiercebroadbandwireless.com/story/35-ghz-spectrum-sharing-effort-could-take-years-produce-results/2012-09-16.

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