Chapter 4
Medium Access Control Protocols in Cognitive Radio Networks

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Abstract The endeavor of categorizing the existing Cognitive-MAC (C-MAC) protocols requires definition of general classification frameworks or layouts that merge most of the aspects of the protocols in a single unified presentation. This chapter introduces the C-MAC cycle as a general classification and systematization layout for C-MAC protocols. The C-MAC cycle originates form the idea that the MAC layer in spectrally heterogeneous environments should provide support for three generic technical features: radio environmental data acquisition; spectrum sharing; and control channel management. The inclusion of these generic technical features is necessary in Cognitive Radio Networks (CRNs) for improving the network performance and achieving spectrum efficiency gain while providing maximal level of protection for the primary system. This chapter presents extensive survey on the state-of-art advances in C-MAC protocol engineering by reviewing existing technical solutions and proposals, identifying their basic characteristics and placing them into the C-MAC cycle, with emphasis on the modularity of the C-MAC cycle. It provides overview of large number of technical details concerning the three generic functionalities (i.e. the radio environmental data acquisition, the spectrum sharing and the control channel management) as the main building blocks of the C-MAC cycle. Three uses cases (each in different generic functional group), illustrate the capabilities of the proposed C-MAC cycle layout. In more detail, the first use case theoretically presents and practically evaluates cooperative spectrum sensing based on Estimated Noise Power. The results illustrate the effect of estimating the noise variance on the detection capabilities of the Majority Voting and Equal Gain Combining cooperative spectrum sensing strategies. The second

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use case presents advanced and computationally efficient horizontal spectrum sharing strategy for secondary systems based on Node Clustering and Beamforming. Finally, the last use case presents and assesses a multiuser quorum-based multiple rendezvous strategy for control channel establishment in distributed Cognitive Radio Networks.

4.1 Introduction

The scientific community has recently experienced rapidly increasing interest in definition and design of Medium Access Control protocols for Cognitive Radio Networks (CRNs). As witnessed, the concept of Cognitive Radio (CR) and CRNs evolved from an abstract and general idea and broad theoretical topic [1] to a set of applicable and practically deployable solutions, some of which entered the process of standardization [2, 3]. These standardization efforts mostly rely on the Dynamic Spectrum Access (DSA) concept (which achieved the status of synonym for CRN) and most networking solutions related to CRN standardization focus on enabling efficient operation in opportunistic i.e. DSA environments. However, the CR as introduced in [1] is envisioned as versatile and dynamically adaptable technology enabler, capable of learning and reasoning possessing the key potential for improving the efficiency and quality of the wireless communication in various different environments and operational settings.

The main distinctive characteristic considering the radio environmental conditions where CRNs (i.e. the secondary systems) operate is the variable availability of the spectrum resources in time, space and frequency [4], a phenomenon commonly referred as **spectrum heterogeneity**. Its behavior and characteristics are the main factors that determine the secondary system performance, the level of protection of the licensed wireless network (i.e. the primary system) and the overall spectrum efficiency gain. The spectrum heterogeneity imposes redefinition of the protocol stack (especially the lower layers i.e. the physical, Medium Access Control and network layer) by introducing new communication protocols. Additionally, cross layering and tight operation coupling between the layers of the stack is highly recommended to achieve better secondary system performances. The novel cross layering-enabled communication protocols address the spectrum heterogeneity by primary system behavior monitoring and transparent adapting to the variable spectrum availability and network topology.

This chapter focuses on MAC protocols designed for CRNs i.e. **Cognitive-MAC (C-MAC)** protocols. In particular, it emphasizes their overall importance for efficient operation of CRN, highlights their basic features with respect to the operational settings and identifies the main challenges concerning the design of C-MAC protocols that enable large spectrum efficiency gains. Summarizing the recent research achievements [4–7], each C-MAC protocol that efficiently addresses the spectrum heterogeneity, should provide support for the following functional requirements [8]:

1. *Primary system protection*. The secondary system should provide maximal protection for the primary system. It should not disrupt the communication links of the primary users by defining strategies for secondary-to-primary interference avoidance and mitigation for attaining the required transparency.
2. *Access to radio environmental information*. The radio environmental knowledge should be acquired by enabling high fidelity spectrum sensing mechanisms and/or access to up-to-date radio environmental information stored in databases. This radio context information should serve as the main enabler of radio environmental awareness.
3. *Advanced spectrum sharing techniques*. C-MAC is responsible for enabling efficient and dynamic spectrum access and resource allocation which aims to increase the overall performance of secondary system by exploiting advanced and intelligent spectrum sharing techniques. Additionally, efficient spectrum sharing strategies should also serve as a facilitating tool for primary system protection.
4. *Control signaling mechanisms*. Fully operational C-MAC protocol requires efficient management and reliable dissemination of control data through identification, definition, establishment and management of reliable and secure control channel.

Addressing and meeting these functional requirements is of high importance towards increasing the overall spectrum efficiency by smart exploitation of its current underutilized space/time/frequency regions. Plethora of proposals, strategies and fully operational and efficient C-MAC solution has been reported in the literature. Most of these proposals address some subset of the following implementation challenges and research topics related to the aforesaid functional requirements: cooperative spectrum sensing, multiband operation, coordination among network nodes, spectrum access and allocation by exploiting advanced artificial intelligence and optimization techniques, secondary-to-primary but also primary-to-secondary interference mitigation and avoidance, multi-channel hidden terminal problem resolving, control channel configuration and reconfiguration, mobility, security, QoS support, scheduling, ARQ procedures etc. Traditionally, the distinction between the different MAC protocols, their classification and systematization is performed on a basis of the employed medium access scheme [9]. However, such practice in the case of C-MAC protocols is practically impossible due to the multidimensional nature of the C-MAC protocols which try to address and meet several conflicting and contradictory requirements as a result of spectrum heterogeneity. The classification of existing C-MAC protocols requires definition of general classification frameworks or layouts that merge most of the aspects of the protocols in a single unified presentation. Such generic layout should provide firm understanding of the protocol operation and it should serve as facilitating tool for the future C-MAC protocol engineering process.

This chapter presents the C-MAC cycle as a general classification and systematization layout for C-MAC protocols [8]. The C-MAC cycle originates form the idea that the MAC layer in spectrally heterogeneous environments should provide support for three generic functionalities: radio environmental data acquisition and knowledge building for radio environmental awareness; efficient radio resource sharing i.e. spectrum sharing; and efficient control channel management. The chapter also provides brief survey on the state-of-art advances in C-MAC protocol engineering by reviewing existing technical solutions and proposals, identifying their basic characteristics and placing them into the C-MAC cycle, with emphasis on the modularity of the C-MAC cycle. It gives an overview of large number of technical details concerning the three generic functionalities and the related functionality-specific and common aspects. Three uses cases (each in different generic functional group), stemmed from authors' previous experience in the area, illustrate the capabilities of the proposed C-MAC cycle layout. In more detail, the first use case theoretically presents and practically evaluates cooperative spectrum sensing based on Estimated Noise Power. The results illustrate the effect of estimating the noise variance on the detection capabilities of the Majority Voting and Equal Gain Combining cooperative spectrum sensing strategies. The second use case presents advanced and computationally efficient horizontal spectrum sharing strategy for secondary systems based on Node Clustering and Beamforming. Finally, the last use case presents and assesses a multiuser quorum-based multiple rendezvous strategy for control channel establishment in distributed Cognitive Radio Networks.

The rest of the chapter is organized as follows. Section 4.2 summarizes the existing C-MAC classification and systematization attempts, highlighting their major drawbacks. Section 4.3 presents the structure and the main motivation behind the C-MAC cycle as generic C-MAC protocol classification layout. Section 4.4 briefly overviews the three generic functionalities of the C-MAC cycle i.e. the spectrum sensing, sharing and control channel management. Section 4.5 presents the C-MAC cycle use cases. Section 4.6 concludes the chapter.

4.2 C-MAC Protocol Classification and Systematization

Several C-MAC protocol classification attempts have been reported in the literature [10–13]. They reflect the state-of-the-art research and standardization achievements in CR networking, differentiate MAC protocols designed for CRNs from MAC protocols designed for legacy wireless networks and attempt to identify general C-MAC classification and systematization criteria. Table 4.1 summarizes the reported criteria used for C-MAC classification in recent publications.

There are several major drawbacks and limitations in these classification proposals. In particular, they generally focus on and tend to cover only some specific set of C-MAC features. Focusing on a subset of C-MAC protocol features and rendering all the existing work on the topic through them, while partially or completely circumventing and ignoring other equally important aspects, results in loss of generality and creation of confusing semantics.

Table 4.1 Proposed C-MAC classification criteria [10–13]

According to	Solutions	Classification based on
Network infrastructure (architecture based)	Centralized or distributed	Location of spectrum management entity
Spectrum resource management	Centralized spectrum access networks or centralized spectrum allocation networks	Role of centralized network entity (only for centralized approaches)
Control channel establishment	Global, local, configurable, w/o dedicated control channel	Presence, scope and characteristics of the control channel (only for distributed approaches)
Spectrum sensing technique	Local or cooperative	Degree of mutual nodes' interactions
Spectrum access modes	Contention-based, time-slotted or hybrid	Secondary nodes spectrum access
Spectrum usage strategy	Single channel or multi-channel	Number of channels available to the secondary nodes
Spectrum sharing modes	Overlay, underlay or interweave	Degree of cooperation between primary and secondary
Number of radios	Single radio or multi radio	Number of radios available to the secondary nodes
Optimization and learning (network coordination)	Direct Access Based (DAB) protocols or Dynamic Spectrum Allocation (DSA) protocols	Degree of optimization scope

The existing literature does not provide systematization and classification layout with unified presentation of all generic (*fundamental*) and *optional* functionalities supported by efficient and reliable C-MAC protocols. The next section introduces the C-MAC cycle, designed to alleviate this deficiency.

4.3 Generic C-MAC Protocols Layout: The C-MAC Cycle

A general C-MAC classification layout should address the following requirements: it should provide firm understanding of the protocol operation; it should be modular, flexible and easily extensible; and it should serve as a future protocol design facilitating tool. The proposed C-MAC cycle [8] meets all of these requirements. The main underlying idea that generates the concept of C-MAC cycle is the recognition that a single C-MAC protocol should support and implement at least three ***generic*** functionalities for efficient operation in spectrally heterogeneous environment (Fig. 4.1). These generic functionalities are: *radio environment data acquisition*, the *spectrum sharing* and the *control channel management*. The requirement for their mandatory support distinguishes C-MAC protocols from the common legacy MAC protocols.

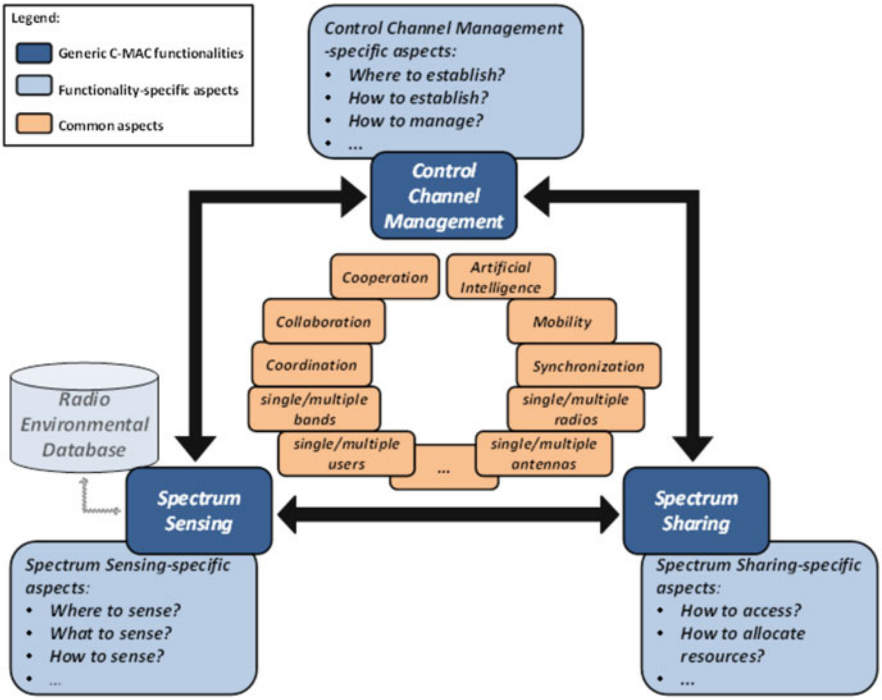

Fig. 4.1 C-MAC cycle [8]

Each of the three generic functionalities is associated to several ***functionality specific aspects*** (i.e. issues that each of the generic functionalities encounters and tends to solve) and common features, techniques and mechanisms referred as ***common aspects***. The distinction between common and functionality specific aspects can significantly improve the flexibility and modularity of the C-MAC cycle. The functionality specific aspects impose challenges and limitations that might be addressed and resolved by using some common techniques and strategies represented by the common aspects. Other than that, the set of common aspects also includes some major limitations imposed on the C-MAC protocols that usually relate to the CR hardware configuration or the operational mode of the network.

The next section overviews the three generic functionalities of the C-MAC cycle, covers their most important functionality specific aspects and discusses the extent to which the common aspects can be utilized to address the functionality specific issues considering the operational settings of the network. The importance of various common aspects (such as optimization, cooperation, coordination among secondary users) for efficient design of C-MAC protocols is specifically highlighted and elaborated throughout the rest of the chapter.

4.4 Overview of the Generic C-MAC Functionalities

This section aims to briefly describe the three generic functionalities of the C-MAC functionalities as well the common techniques and strategies employed to address their specific aspect with respect to the operational settings of the secondary system.

4.4.1 Spectrum Sensing Strategies

There are two possible ways to obtain the radio environmental information and knowledge: via spectrum sensing (sensing-centric) or through an access to a radio environmental database (database-centric). The spectrum sensing is a physical layer functionality that is tightly coupled with the MAC layer and is perceived as the basic tool in CR for acquiring radio environmental data in the sensing-centric CR solutions. The data provided by the spectrum sensing functionality should provide reliable and up-to-date information on the spectrum occupancy, availability and usage. In the database-centric solutions, the radio context information is obtained through access to remote and (logically) centralized up-to-date environmental database. In this case the spectrum sensing functionality may be completely absent and the existence of a control channel mechanism for accessing and obtaining spectrum data from the central database, fulfils the radio environmental awareness requirement. Thus, when operating in database-centric mode, the spectrum sensing functionality is not mandatory. However, its implementation can be beneficial for improving the secondary system performance in general. Furthermore, enabling the spectrum sensing functionality is a challenging task that attracts attention by both, the industry and the research community. Therefore, this chapter focuses on the spectrum sensing functionality of the CMAC cycle.

4.4.1.1 Types of Spectrum Sensing

The main goal of the spectrum sensing functionality as a part of the C-MAC protocol is the discovery and the constant tracking of the spectrum opportunities for the operation of the CRN. The detection of spectrum opportunities can be performed via signal detection and classification. The ***signal detection techniques*** reported in the literature are classified in two broad classes: blind and feature detection techniques [14]. The *blind detection techniques* are used to blindly detect the presence or the absence of any type of signal in the wireless medium without any prior knowledge on the type and structure of the underlying primary user signals. Typical representatives of the class of blind detection techniques are the energy detection, the detection based on autocorrelation and the Higher-Order-Statistics detection [15]. The *feature detection* methods, in addition to the detection of signal existence, have the ability to perform signal classification, and hence, distinguish primary from secondary users' signals, as well as distinguish between different types of primary and secondary user signals. Typical examples of feature detection techniques are the matched filter and cyclostationarity detection techniques. In *cooperative environments* [14, 16], individual spectrum observations can be fused into joint primary user signal existence decision by the means of using hard and soft ***decision fusion techniques***. In the case of *soft decision fusion*, the individual observation samples are summed using Equal Gain Combining (EGC), Maximum Ratio Combining (MRC) techniques, as well as other more advanced weighted based combining techniques [17], before making the decision on the signal presence. In *hard decision fusion* methods, such as AND, OR, M-out-of-N rules, Chair-Varshney fusion rule [18], individual decisions of the cooperating nodes are cooperatively fused into joint primary user decisions.

There are several general types of spectrum sensing depending on the spectrum sensing-specific aspect taken into account. With respect to the ***sensing execution time***, there are two types of spectrum sensing: reactive (on-demand) and proactive (periodic) sensing [2, 19]. The *reactive sensing* serves for spectrum opportunity discovery and it might be triggered by the radio environmental changes. The *proactive sensing* is used for persistent search and tracking of spectrum opportunities as well as estimating primary user activity patterns and traffic characteristics. Regarding the ***bands of interest*** for the secondary system, two types of sensing can be distinguished: in-band sensing and out-of-band sensing [2, 19]. The *in-band sensing* tracks for primary user signals and attempts to avoid harmful collisions on the same channel where secondary data transfer occurs. Oppositely, the *out-of-band sensing* aims to discover new opportunities for secondary usage. Based on the ***number of sensed bands***, the spectrum sensing is usually divided into two broad classes: single-band and multiband sensing [20]. In *single-band* mode, the spectrum sensing functionality senses and tends to discover secondary transmission opportunities in a single primary user band. On the other hand, when *multi-band sensing* is enabled, the spectrum sensing explores multiple legacy bands which results in increased flexibility and improved efficiency. However, the implementation of multi-band sensing is more complex and challenging.

4.4.1.2 Optimization of the Spectrum Sensing

In order to provide improved secondary system performances and additional spectrum efficiency gain, the spectrum sensing functionality should be optimized. In most cases, the spectrum sensing optimization goal is multi-objective resulting in multidimensional optimization problem with a number of (very often conflicting) constraints. The proposed strategies for sensing optimization usually rely on the common aspects of the C-MAC cycle and they can be classified (as shown on Table 4.2) in three general categories: strategies for single-band or multiple bands (non cooperative environments) and strategies for cooperative environments.

For **non-cooperative single-band** enabled environments, the common optimization parameters are the ***sensing period duration*** and the ***transmission period***

Table 4.2 Spectrum sensing optimization

Sensing optimization			
Non-cooperative environments			
Single-band	Multiple bands		Cooperative environments
Sensing time duration	Sensing Policies	Channel set Channel number Channel sensing order	Node selection
Transmission time duration	Stopping rule		Node clustering
Sensing errors	Exploration-exploitation trade-off		Channel selection

duration. The duration of the sensing period is tightly related to the reliability of the sensing, e.g. the probability of detection of a primary user signal and the probability of false alarm. However, the problem of sensing inefficiency arises with increasing sensing period duration. There exist a trade-off between the sensing and transmission periods' durations. Increasing the sensing period duration results in better sensing reliability but also in inefficient use of the transmission opportunities [21], while the increase of the transmission period duration increases the spectrum opportunity usage, but false alarms and miss-detections of primary user signals are more likely to occur. In addition to the sensing reliability related parameters, the optimization of the transmission and sensing periods durations, should also consider the primary system traffic behaviour. This can be done by adopting some predefined primary user channel model with fitted parameters such as the Gilber-Eliot primary user channel model [22].

In **multi-band** enabled environments, the spectrum sensing is optimized by deriving the optimal rules and means to resolve the set, the number and the order of the primary user channels to be sensed. These sets of rules are referred as spectrum sensing policies and they represent the main optimization target in multi-band enabled sensing.

With respect to the ***number of primary user bands*** covered by the spectrum sensing functionality, the sensing policies can be divided into two broad classes [20]. The first class refers to *single-channel sensing policies*, where the secondary user operating in a multi-band environment senses only a single legacy channel and based on the outcome (free or busy), the user decides whether to exploit the channel or to wait for other opportunities. The second class of the sensing policies, which is more challenging, relates to the sequential channel sensing. The CRN nodes adopting the *sequential-channel sensing policies* sense multiple primary user channels, before making the channel selection and access/sharing decisions. While the sequential-channel sensing provides dominant CRN performances, it also requires higher processing power.

In addition to selecting the sensing channel(s), in the case of sequential sensing policies, the ***number of legacy channels*** covered in a single C-MAC round is also crucial parameter [23, 24]. The performance of the sequential sensing depends on the maximum number of channels a CR node can sense in a single C-MAC round. If the CR node is able to employ the *full observation sensing policy* i.e. the CR node is capable of performing the sensing of the full legacy band of interest, the best possible secondary system performance can be achieved. However, employing this sensing policy is not energy efficient. This issue pinpoint the need for more optimal and more efficient spectrum sensing policy (i.e. *green spectrum sensing policy*) [23, 25] that trades-off between the secondary system performance and the energy efficiency of the sensing process.

The ***channel sensing order*** [20, 26] is another important aspect covered by the sensing policies. The optimal channel sensing order selection among the contending secondary users yields a collision free secondary spectrum access. Various strategies and techniques for design of optimal channel sensing orders can be found in the existing literature. For an example, channel sensing orders can be selected randomly from all possible channel permutations, or they can be selected from a Latin square of non-overlapping channel permutations [20]. The sensing order selection process can be aided by learning and other advanced artificial intelligence concepts, efficiently reaching a collision free sensing orders based on the feedback from the spectrum sharing functionality.

Learning is a common C-MAC aspect that can be incorporated in the spectrum sensing policies to improve the performances of the generic C-MAC functionalities and the overall secondary system performances. With respect to the learning capabilities the spectrum sensing policies are divided into non-learning and learning policies. By using *non-learning policies* the CR node aims to perform the selection of sensing channels without considering historical data, such as previous availabilities and opportunities in the pool of legacy channels, as well as the previous outcomes (feedbacks) from the spectrum sharing functionality. Representatives of such non-learning policies are the random sensing policies [27, 28] and negotiation based sensing policies [27]. The *learning based sensing policies* [22, 29, 30] aim to improve the spectrum sensing process in the next C-MAC rounds by using historical data and experience accumulated in previous C-MAC rounds. The learning based sensing policies usually adopt a predefined primary system model and tend to learn the traffic parameters of the model and to do so, they exploit the historical sensing data, as well as the previous spectrum sharing feedbacks. The common primary user channel model extensively used in CR networking is the Gilber-Eliot channel model. Typical representative examples of the learning based policies are the myopic sensing [29, 30] and its variations.

The ***sensing stopping rule*** i.e. the rule that decides when to stop to sense the legacy channels, determines the overall duration of the sensing in multi-band environments and it's therefore a common optimization parameter. The *optimal sensing stopping rule* comes from the economics [31]. The secondary user compares the current reward with the expected reward if the sensing is continued, and stops as soon as the current reward is higher than the expected reward. The reward is a function of the channel observations and usually refers to some secondary system performance metric such as the aggregate secondary throughput calculated on the detected available channels. The current and the expected rewards are calculated using some predefined primary user channel model. When the total number of sensing channels is K and the number of already sensed channels is n, then the current reward is calculated over these n sensed channels and the expected reward is calculated over all K channels including the remaining $K - n$ not sensed channels. This results in complex computations. A complexity reduction solution to the optimal stopping rule is the k-stage look-ahead rule. Instead of calculating the expected reward for all remaining sensing channels from the pool of K possible channels, the k-stage look-ahead rule compares the current reward with the expected reward over the subsequent $k < K$ channels. The authors in [31] show that there is only a slight secondary system performance decrease in the case of 2-stage look-ahead rule, compared to the optimal stopping rule case.

In learning aided multi-band spectrum sensing scenarios, a common trade-off that arises is the ***exploration-exploitation trade-off*** [22, 26]. The secondary user might decide to probe and access the already proven most reliable channels, or it can try to explore new arisen opportunities. This trade-off highly affects the secondary system performances in the cognitive radio environment. A common methodology in the learning aided spectrum sensing and access is to perform the sensing channels selection based on the exploration-exploitation trade-off. Thus, the channels to be sensed can be obtained as an outcome of optimization. The optimization function is usually composed of an exploitation part, which prefers historically most available channels and an exploration part, which in the form of regret penalizes the most often selected channels.

In **cooperative environments**, different secondary users share their sensing outcome to improve the detection performance at the expense of increased latency and communication overhead. The essential optimizations regarding the spectrum sensing in cooperative environments, consider the aspects of node selection, channel selection and node clustering. The node selection and node clustering strategies [32, 33] are similar in the sense that they aim to select a subset of the secondary users based on the nodes' characteristics in order to reduce the sensing latency and control traffic overhead. The channel selection strategies essentially adopt the single user sensing strategies (in terms of the sensing policies, exploration-exploitation trade-off, etc.) and extend them to the multi-user scenarios.

4.4.2 Spectrum Sharing Strategies

The spectrum sharing functionality exploits the radio context information for efficient secondary allocation, access, sharing and utilization of the spectrum opportunities, maintaining the secondary system QoS while providing primary system protection. Thus, in sensing-enabled C-MAC protocols, the performance of the spectrum sharing depends on the reliability of the outcome of the spectrum sensing functionality. The spectrum sharing is tightly related with the control channel management, since all of the required radio context information and

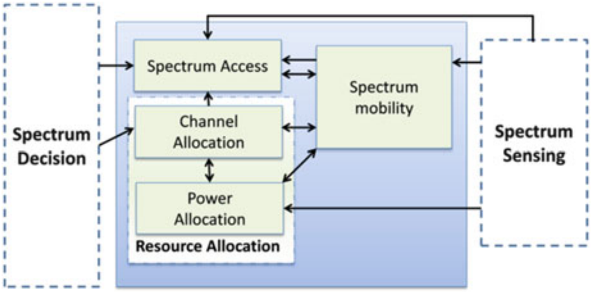

Fig. 4.2 Block diagram of the spectrum sharing processes

spectrum sharing/access decisions should be communicated between the different CRN entities via reliable and secure control channel.

The spectrum sharing techniques are usually classified as vertical and horizontal techniques. The **vertical** techniques refer to opportunistic spectrum access and/or spectrum mobility where the secondary users share the same spectrum band with the primary users, by exploiting the features of *interweave*, *underlay* or *overlay* spectrum sharing. The **horizontal** techniques concern with the inter/intra-network spectrum sharing between the secondary users. Figure 4.2 schematically depicts the main processes related to the spectrum sharing functionality. These generic processes are: resource allocation, spectrum access and spectrum mobility which is of crucial importance when addressing the primary system protection requirement.

The following subsections aim to provide brief description of the most important aspects with respect to the generic spectrum sharing processes.

4.4.2.1 Resource Allocation

The resource allocation comprises two generic processes, the ***channel allocation*** and the ***power allocation*** (Fig. 4.2), which are usually jointly optimized. The channel allocation process is responsible for finding the most suitable frequency and channel bandwidth, whereas the power allocation process is responsible for managing the transmit power of the secondary users in order to satisfy the interference constraints of the primary system. Thus, the resource allocation process relates to resource parameters and resource allocation constraints. The *resource parameters* define the space of optimization of the resource allocation process. There are several types of resource parameters such as spectrum related parameters (i.e. frequency, bandwidth, etc.), physical layer parameters (modulation, coding, power, antenna configuration, etc.) and higher layer parameters (scheduling, buffer management, ARQ, etc.). The set of *resource allocation constraints* is in general, scenario specific and depend on the underlying CR use-case. However, they always relate to either of the two generic C-MAC functional requirements: primary system protection and maintaining the secondary system QoS.

Regarding the optimization the problem of resource allocation is multi-objective. The latest advances in the area of resource allocation optimization focus on two distinct methodologies: the classical methods and metaheuristcs based optimization algorithms. *Classical optimization methods*, like *single-variable* and *multivariable optimization*, convert the multi-objective optimization problems in a single-objective problem using a preference-based strategy and therefore they are usually inappropriate for solving the resource allocation problem. Oppositely, the *meta-heuristcs* based algorithms utilize a population of solutions instead of focusing on a single one which makes them very suitable for solving multi-objective optimization problems. The most commonly utilized metaheuristcs based algorithms in terms of the resource allocation process vary from *ant colony optimization* [34] and *Swarm intelligence algorithms* [35] up to *Genetic algorithms* [36], *Differential evolution* [37] and *Simulated annealing algorithms* [38].

4.4.2.2 Spectrum Access

The spectrum access enables both the vertical and horizontal spectrum sharing by using CRN suitable multiple access protocols and is tightly related to the spectrum decision and channel allocation processes as well as the spectrum sensing functionality outcome. The multiple access techniques in CRN, rely on and exploit the features of the common multiple access protocols (extensively used in legacy wireless systems) such as Carrier Sense Multiple Access (CSMA) [39], Orthogonal Frequency Division Multiple Access (OFDMA) [40], Space Division Multiple Access (SDMA) [41], Ultra-Wideband/Code Division Multiple Access (UWB/CDMA) [42], Time Division Multiple Access/Frequency Division Multiple Access (TDMA/FDMA) [43] and Dynamic Frequency Hopping (DFH) [44]. Table 4.3 summarizes the most important aspects of multiple access techniques in the context of CRN.

The spectrum access can be either autonomous or coordinated. The ***autonomous spectrum access*** is accomplished by achieving individual goals like the QoS requirements [27, 45] or the energy consumption [46] of a given secondary user. Additionally, it may employ learning techniques based on past decisions and outcome, which ultimately can increase the system throughput [47] and achieve autonomous load balancing [20]. The ***coordinated spectrum access*** is more efficient in terms of the achievable CRN performance and requires more complex C-MAC protocols. As an example, in centralized scenarios the C-MAC can manage the process of sharing the primary system environmental knowledge, which can yield increased spectrum awareness [27], but will inevitably increase the implementation complexity.

Table 4.3 Multiple access schemes comparison

	CSMA	OFDMA	SDMA	UWB/CDMA	TDMA/FDMA	DFH
Sharing strategy	Interweave/underlay	Interweave/underlay	Underlay/overlay	Underlay	Interweave/underlay	Interweave
Multiple access dimension	Time	Frequency	Space	Spread spectrum	Time/frequency	Time/frequency
PU protection	Collision avoidance/ interference threshold	Collision avoidance/ interference threshold	Interference mitigation/ interference alignment/ cooperation	Interference threshold	Collision avoidance/interference threshold	Collision avoidance
Requirement from the spectrum sensing	Available frequency bands/available power mask	Available frequency bands/available power mask	Fading gains between SUs and PUs/available power mask	Available power mask	Available time slots/frequency bands/available power mask	Available frequency bands
Implementation complexity	Low/moderate	Moderate	High	High	Moderate	low
Computation complexity	Low/moderate	Moderate/high	High	High	Moderate	low

4.4.2.3 Spectrum Mobility

The spectrum mobility is a direct facilitator of the primary system transparency requirements and enabler of the concept of frequency agility which results in increased secondary system performances. The spectrum mobility can be realized through four types of spectrum handovers: static, reactive, proactive and hybrid [48].

In the case of ***static*** spectrum the secondary system will stay on the same channel and not transmit until the same channel becomes free again. The biggest setback of this spectrum handover type is the high secondary system latency incurred by the transmission of the primary system. In ***reactive*** spectrum handovers, the secondary user vacates the licensed channels after the reappearance of a primary user. The efficiency of the reactive spectrum handovers is tightly related to the handover latency. The ***proactive*** spectrum handovers utilize some predictive methods that trigger when the secondary users must vacate the underlying channel which minimizes both, the handover latency and the number of future spectrum handovers. These types of spectrum handovers can potentially benefit from learning and prediction, where the CRN can learn the environment dynamics, predict undesirable situations and act to avoid such situations in timely manner [49]. However, employing learning and prediction techniques increase the computational complexity. Finally, the ***hybrid*** spectrum handovers represent a compromise between the high latency (reactive spectrum handovers) and high complexity (proactive spectrum handovers). Typical representative of the hybrid approaches is the Incumbent Detection Recovery Protocol (IDRP) used in IEEE 802.22 WRAN standard [2].

4.4.3 Control Channel Management Strategies

The control channel (CC) is used for exchange and dissemination of different types of sensing and sharing related data (such as spectrum sensing outcome, sharing decisions, channel access feedback, etc.) between the different entities in the CRN. Thus, the CC provides its services to number of CRN operational aspects such as network self-organization, network coordination, synchronization, cooperation, collaboration, spectrum mobility, flexible data connections and increasing and attaining overall spectrum efficiency [50]. However, due to spectrum heterogeneity, the CC management functionality in C-MAC, encounters several major issues, not present in the legacy C-MAC protocols. CC variable availability, saturation, coverage, security are among the most common CC design challenges that require addressing. Depending on the target application and operational mode of the CRN, the CC management functionality of the C-MAC protocol should decide how to establish the CC to mitigate the mentioned problems [51]. This section briefly covers several popular techniques for CC establishment in spectrally heterogeneous environments.

The CC can be established as either Dedicated or Non-dedicated. The **Dedicated CC (DCC)** solutions refer to CC establishments where a set of secondary spectrum resources are solely dedicated for the transport of secondary system control information. The DCC is usually realized as a Global, Local or Dynamic. When establishing ***Global DCC (GDCC)*** [31], set of primary user channels are globally allocated for the CC and the secondary users tune to these channels to exchange control information. The ***Local DCC (LDCC)*** is similar to the GDCC except that it is established locally, on secondary users group [52], or a secondary user cluster level [53]. The LDCC alleviates the single point of failure effect exhibited by the GDCC. When both, the GDCC and the LDCC establishments adapt to the varying primary network conditions, the ***Dynamic DCC (DDCC)*** is established [54]. Although, the DDCC provides largest secondary system performance gain, it is also the most complex DCC establishment.

The other group of technical solutions for CC establishment consists of **Non-Dedicated CC** (NDCC) proposals. In the NDCC enabled CRN, the secondary users share the available channels of the target licensed band for exchange of both control and data packets. The NDCC can be established by Frequency Hopping, Rendezvous or as Ultra-Wideband. When establishing ***Frequency Hopping NDCC (FHNDCC)*** [55], the secondary users hop across the available channels to exchange control information, using a predetermined hoping list. However, this solution requires tight synchronization. When using ***Rendezvous NDCC (RNDCC)*** [56], the secondary users hop across the channels using different hoping lists that overlap multiple times. Thus, the RNDCC can be either synchronous or asynchronous. One of the main parameters of interest in RNDCC establishments is the Time-to-Rendezvous (TTR) denoting the average time that elapses until the first overlap occurs. The hopping lists should be designed to minimize the TTR while providing as many overlaps as possible. The last CC establishment is via Ultra-Wideband technology. The ***Ultra-Wideband NDCC (UWBNDCC)*** [57] is established in underlay fashion, by spreading the control information over the whole disposable band. However, this establishments suffers from all common drawbacks of UWB technology such as limited transmission range, interference to the primary system etc. Table 4.4 summarizes the discussed characteristics and behaviours of the various CC establishments.

The following section presents three particular C-MAC algorithms. Each of them fit in specific generic area (i.e. spectrum sensing, spectrum sharing and control channel management) and implement different specific functionalities, placing them in the generic C-MAC cycle layout. Besides emphasizing the specifics of the C-MAC protocol design process for a particular operational scenario, the use cases also serve as an illustration of the potential benefits of applying the C-MAC cycle on certain C-MAC protocols in terms of understanding the range of applicability of the protocols and their basic operational limitations.

Table 4.4 Qualitative comparison of various control channel establishments techniques

	Dedicated control channel			Non-dedicated control channel		
Establishment	Global	Local	Dynamic	Frequency hopping	Rendezvous	Ultra wideband
Saturation susceptibility	High	Medium	Low	Medium-low	Low	High
PU activity robustness	Low	Medium	High	High	High	High
Coverage	Global	Local	Global/local	Link-based	Link-based	Global/local
Security attacks resilience	Low	Medium-low	High	High	High	Medium-low
Configuration delay	Low	Medium-high	Medium-high	Medium	Low-medium	Medium
Access delay	Low	Low	Low	High	High-medium	Low

4.5 C-MAC Cycle Use Cases

This section presents three chosen C-MAC cycle use cases, aiming to elaborate the implemented functionalities in each of them. They were chosen to illustrate particular generic C-MAC features (elaborated in Sect. 4.4). In particular, Sect. 4.5.1 presents the cooperative spectrum sensing based on Estimated Noise Power as a representative of the spectrum sensing Sect. 4.5.2 introduces a horizontal spectrum sharing strategy for secondary systems based on Node Clustering and Beamforming, as a representative of a spectrum sharing. Finally, Sect. 4.5.3 analyzes, assesses and explains the modularly merged within the C-MAC cycle of the multiuser quorum-based multiple rendezvous strategy for control channel establishment in distributed Cognitive Radio Networks. These C-MAC cycle use cases are selected in a relation to the expertise of the authors in the area of C-MAC protocol engineering and they are result of the authors' recent work in this area.

4.5.1 Cooperative Spectrum Sensing Based on Estimated Noise Power

Spectrum sensing has been pinpointed as one of the facilitating technologies for spectrum opportunities detection in Dynamic Spectrum Access (DSA) and CR systems. Although the latest developments in CR regulation favor the database approach [1], spectrum sensing can provide reliable opportunistic access in many scenarios (e.g. dynamic and unpredictable environments [58]). Under these circumstances, the efficiency and reliability of the spectrum sensing approach can prove to be crucial in providing the required system performance to the underlying cognitive radio network. More accurate and efficient spectrum sensing results in higher spectral utilization of the secondary user system as well as in lower interference to the incumbent system. The Cooperative Spectrum Sensing (CSS) approach increases the sensing performance by exploiting the spatial diversity from multiple secondary user sensing nodes.

This subsection focuses on a C-MAC cycle use case regarding the Cooperative Spectrum Sensing process. More specifically it elaborates on a specific Cooperative Spectrum Sensing approach which utilizes the aspects of Noise Power Estimation (ENP). Figure 4.3 depicts the C-MAC instantiation of the *Cooperative Spectrum Sensing based on ENP*. This approach is designed to perform single band spectrum sensing and exploit the sensed information from multiple CR users. The CSS based on ENP approach heavily depends of the cooperative/collaborative aspects of the C-MAC cycle and tightly relates to the synchronization feature (as a facilitator of the cooperation and collaboration process). The remainder of this subsection will elaborate and discuss in more details the CSS based on ENP and its relation to the C-MAC protocol.

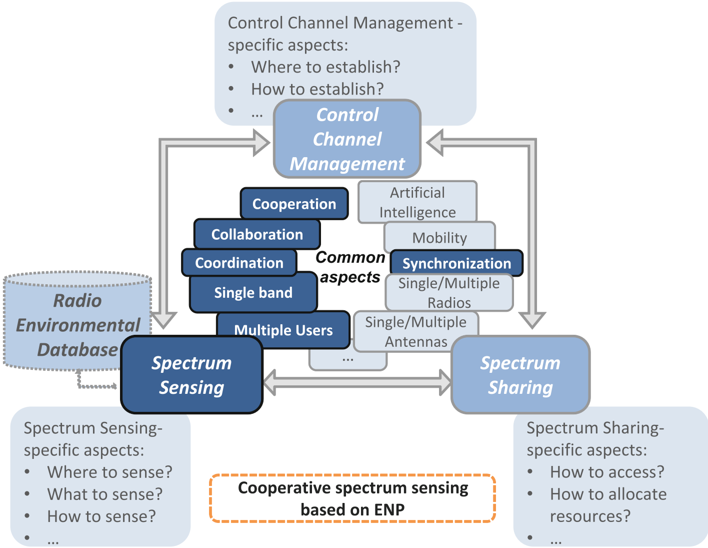

Fig. 4.3 CSS based on ENP C-MAC cycle instantiation

4.5.1.1 The ENP Theory

Regarding the spectrum sensing process, the simplest method capable of detecting the presence of a primary user is based on the energy detection notion. The Energy Detector (ED) is most optimal when there is no information about the primary user (i.e. no feature detection can be performed). Likewise, the ED is appropriate for fast and wideband spectrum sensing where different kinds of signals exist. The ED performance has been studied in many works where the receiver has perfect knowledge about the noise power. However, in practical receivers (spectrum sensors) it is impossible to have perfect knowledge about the noise power level. A set of works have addressed this problem [59, 60] stating that there exists a minimum value of SNR under which the detection is not possible even for infinite number of sensed samples. This phenomenon is known as the SNR wall. It has been preserved as an inexorable problem, since the estimation of the noise power always differs from the real noise power [61]. Recent studies [62, 63] have proved that the SNR wall is not caused by the presence of an uncertainty in the noise power itself, but by insufficient information about the noise power estimation. The authors in [62] propose an approach that is capable of alleviating the SNR wall by utilizing higher number of noise-only samples, called the *Estimated Noise Power (ENP)*. The work in this subsection extends the given theory by introducing the aspects of Equal Gain Combining (EGC) and Majority Voting (MV) cooperative spectrum sensing to the ENP approach.

4.5.1.2 System Model and Analytical Relations

This section briefly describes the system model used for deriving the analysis of the proposed CSS approach and derives analytical forms for the probability of detection and probability of false alarm for the EGC and MV techniques. The system model assumes signal detection in an AWGN channel where the ith received signal sample under both hypotheses is given as:

$$y_i = \begin{cases} n_i, & H_0 \\ x_i + n_i, & H_1 \end{cases} \tag{4.1}$$

where H_0 and H_1 denote the signal's absence and signal's presence hypothesis, respectively. The signal sample x_i and noise sample n_i are circularly-symmetric complex Gaussian random variables with zero mean and variances: $2S$ and $2\sigma^2$, respectively. Based on Eq. (4.1) and assuming an energy detector, the detection problem can be defined as a log likelihood ratio test:

$$\Lambda_g(y) = \frac{1}{2\sigma^2}\frac{1}{N}\sum_{i=0}^{N-1}|y_i|^2 \begin{matrix} > \xi & H_1 \\ < \xi & H_0 \end{matrix} \tag{4.2}$$

where N denotes the number of sensed samples and represents the decision threshold. For a predefined value of the probability of false alarm (P_{fa}) and number of sensed samples (N), the detector must know the noise variance in order to set its decision threshold ξ. Because in practical implementations the energy detector utilizes only an estimate, instead of the true noise power (i.e. variance) the likelihood ratio test is defined as the generalized likelihood ratio test when no a priori knowledge about the primary signal is available:

$$\Lambda_g(y) = \frac{1}{2\hat{\sigma}^2}\frac{1}{N}\sum_{i=0}^{N-1}|y_i|^2 \begin{matrix} > \xi & H_1 \\ < \xi & H_0 \end{matrix} \tag{4.3}$$

where $\hat{\sigma}^2$ denotes the noise power estimates and depends only on the specific estimation technique in use. In the proposed system model, the noise power samples at the receiver are estimated utilizing the ML approach:

$$\hat{\sigma}^2_{ML} = \frac{1}{2M}\sum_{i=1}^{M}|n_i|^2 \tag{4.4}$$

where n_i denotes the noise samples, while M refers to the number of sensed noise samples. As discussed in [62, 63], the $\hat{\sigma}^2_{ML}$ estimator represents an effective noise estimator capable of reaching the Cramer-Rao bound.

Based on these system model assumptions and as elaborated in [63], the probability of detection ($Q^{EGC}_{d\_ENP}$) and probability of false alarm ($Q^{EGC}_{fa\_ENP}$) for the

EGC based ENP approach are defined as:

$$Q_{d\_ENP}^{EGC} = Q\left(\frac{\frac{\xi}{1+SNR} - 1}{\sqrt{\frac{M+N}{KMN}}}\right) \tag{4.5}$$

$$Q_{fa\_ENP}^{EGC} = Q\left(\frac{\xi - 1}{\sqrt{\frac{M+N}{KMN}}}\right) \tag{4.6}$$

where $Q(\cdot)$ denotes the Q-function, while *SNR* and K represent the received *SNR* at the CR node and the number of cooperating nodes respectively. Similarly the probability of detection ($Q_{d\_ENP}^{MV}$) and probability of false alarm ($Q_{fa\_ENP}^{MV}$) for the MV based ENP approach are defined as:

$$Q_{d\_ENP}^{MV} = \sum_{i=K/2}^{K} Q\left(\frac{\frac{\xi}{1+SNR} - 1}{\sqrt{\frac{M+N}{MN}}}\right)^{i} Q\left(\frac{\frac{\xi}{1+SNR} - 1}{\sqrt{\frac{M+N}{MN}}}\right)^{K-i} \tag{4.7}$$

$$Q_{fa\_ENP}^{MV} = \sum_{i=K/2}^{K} Q\left(\frac{\xi - 1}{\sqrt{\frac{M+N}{MN}}}\right)^{i} Q\left(\frac{\xi - 1}{\sqrt{\frac{M+N}{MN}}}\right)^{K-i} \tag{4.8}$$

where $Q(\cdot)$ denotes the Q-function, while *SNR* and K represent the received *SNR* at the CR node and the number of cooperating nodes respectively. From Eqs. (4.5) to (4.8) it is evident that the CSS based on ENP represents a complex process which exploits a set of *different sensing parameters* (e.g. number of sensed samples, number of noise samples, number of cooperating users, threshold adaptation). This implies that the C-MAC protocol must perform an “intelligent” selection of the given sensing parameters in order to achieve the required detection performance. The following subsection elaborates on the performance analysis (i.e. numerical and experimental validation) of the proposed CSS based on ENP approach.

4.5.1.3 Performance Analysis

This section briefly discusses the performance of the EGC and MV cooperative spectrum sensing techniques when utilizing the ENP theory and validates the theoretical assumptions with experimental results. The analysis is performed in terms of the ROC curve, average Bayesian risk and detection probability. Moreover, the values of the input parameters (i.e. K, N, M, etc.) in the analysis are selected based on practical investigations and on the studies made in previous works

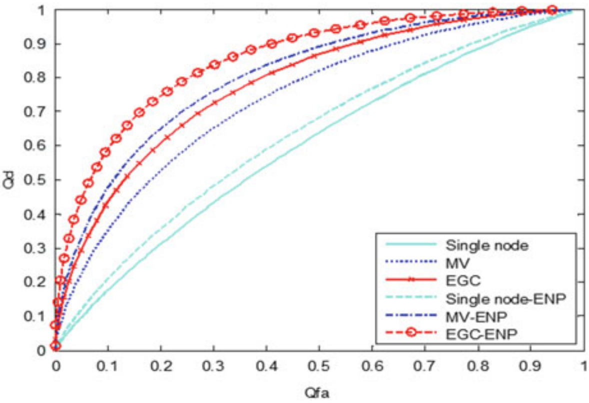

Fig. 4.4 ROC curve ($N = 10^6$, $M = 10N$, $K = 10$, $SNR = 5 * 10^{-4}$) [64]

regarding the ENP approach [62,63]. In order to simplify the notation, the MV based ENP and EGC based ENP techniques will be noted as MV_ENP and EGC_ENP, respectively.

Figure 4.4 delineates the ROC curves for single node detection and for both EGC and MV techniques. As seen from the figure, the non-cooperative case (without the ENP approach) achieves the worst, while the EGC_ENP achieves the best ROC performance. It is also evident that MV_ENP outperforms the classical EGC fusion rule due to the utilization of the ENP approach.

Figure 4.5 depicts the average Bayesian risk in terms of the number of sensed signal samples N. The average Bayesian risk defines the overall performance of the cooperative spectrum sensing and can be expressed as follows:

$$\overline{R} = P(H_0)Q_{fa}C_{10} + P(H_1)(1 - Q_d)C_{01} \tag{4.9}$$

where $P(H_0)$ and $P(H_1)$ represent the probability of primary user absence and presence, respectively, while C_{10} and C_{01} denote the price coefficients when making a wrong decision (in this work $C_{10} = C_{01} = 1$) and are used to model the system behavior and type [63].

It is evident from Fig. 4.5 that EGC_ENP achieves the best performance, i.e., the smallest Bayesian risk, while the non-cooperative case without ENP incorporates the highest Bayesian risk, i.e., worst performance. Similarly to the conclusions from the previous figure, MV_ENP outperforms the classical EGC and achieves lower Bayesian risk.

In order to validate the CSS based ENP theory, the analytical models of the EGC_ENP and MV_ENP are compared to experimental results regarding the probability of detection. Figure 4.6 depicts the theoretical vs. experimental results regarding the EGC_ENP approach and proves the validity of derived EGC_ENP analytical models. Moreover, it can be noticed that the EGC_ENP has a constant 3 dB detection performance increase with each sample size quadrupling.

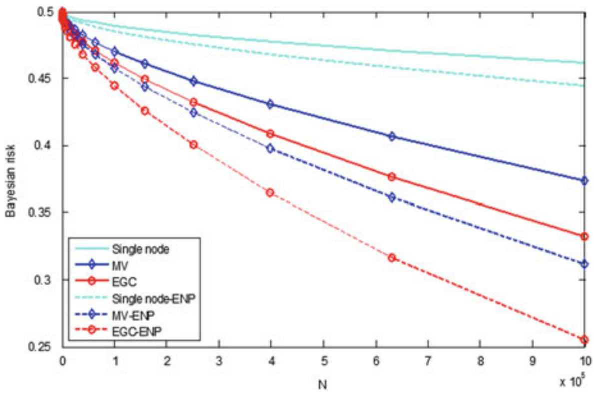

Fig. 4.5 Average Bayesian risk in dependence of the number of sensed samples N ($M = 10N$, $K = 10$, $Q_{fa} = 0.1$, $SNR = 5 * 10^{-4}$, $P(H_0) = 0.5$) [64]

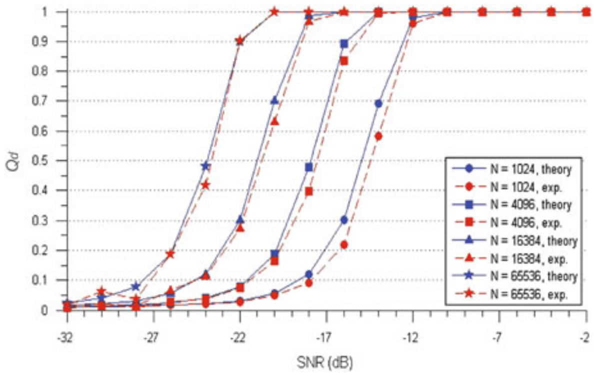

Fig. 4.6 Q_d vs. SNR theoretical and experimental EGC_ENP result ($K = 5$, $M = 10^7$, $Q_{fa} = 1\,\%$)

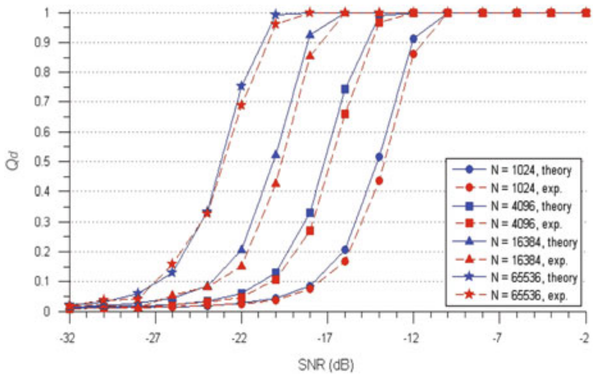

Fig. 4.7 Q_d vs. SNR theoretical and experimental MV_ENP result ($K = 5$, $M = 10^7$, $Q_{fa} = 1\,\%$)

Figure 4.7 depicts the theoretical vs. experimental results regarding the MV_ENP approach and proves the validity of derived MV_ENP analytical models. Similarly to the conclusions from the previous figure, the MV_ENP achieves a constant 3 dB detection performance increase with each sample size quadrupling.

The subsection presented a specific C-MAC cycle use case regarding the spectrum sensing process which exploits the features of CSS and introduces the aspect of ENP. As discussed, the CSS based on ENP represents a multifaceted process which utilizes a variety sensing parameters that need to be governed in the most efficient manner from the C-MAC in order to achieve the required performance. This C-MAC related task tightly relates to the requirements and goals of the underlying use-case scenario. For example, in many cases the best sensing setup is optimal for achieving the best signal detection performance, however can be suboptimal regarding other system related performances like, throughput, packet delay, etc. Therefore, it is more efficient for the C-MAC to coordinate and optimize the sensing process regarding the system parameters of interest, rather than the signal detection. In this case the C-MAC related optimization can be based on the derived and validated analytical models for the probability of detection and probability of false alarm of the EGC_ENP and MV_ENP approaches.

4.5.2 Coordinated Beamforming for Spectrum Sharing

To guarantee high spectrum efficiency while mitigating the interference to the primary users, the CR should be able to adapt to the spectrum conditions flexibly. However, the interference caused by horizontal spectrum sharing becomes an obstacle that limits the system performance, such as the system throughput. Thus, in horizontal sharing, the goal is to try to find a way to decrease the inter-system interference (i.e. collisions) and increase its system throughput. The cooperation between the secondary systems can additionally increase the spectrum efficiency of the horizontal sharing process. One possible approach that is based on cooperation and can provide high spectrum utilization is the Space-Division Multiple Access (SDMA) approach.

This subsection elaborates on a specific C-MAC cycle use case regarding the horizontal spectrum sharing process. The given use case, entitled *Network Coordinated Beamforming with user Clustering (NCBC)* [65], utilizes the concept of SDMA via Network Coordinated Beamforming (NCBF) and user Clustering. Figure 4.8 depicts the C-MAC instantiation of the NCBC. This approach is envisioned to perform single band spectrum sharing and exploit the spatial diversity from multiple antennas and CR users. The NCBC depends of the cooperative/collaborative aspects of the C-MAC cycle and tightly relates to the distribution features of the C-MAC protocol in order to achieve the required system performance. The remainder of the subsection will discuss in more details the NCBC and its relation to the C-MAC protocol.

4.5.2.1 System Model

The system model considers the case where a set of K secondary CR (secondary user) systems coexist and share the same spectrum (frequency band). It is assumed

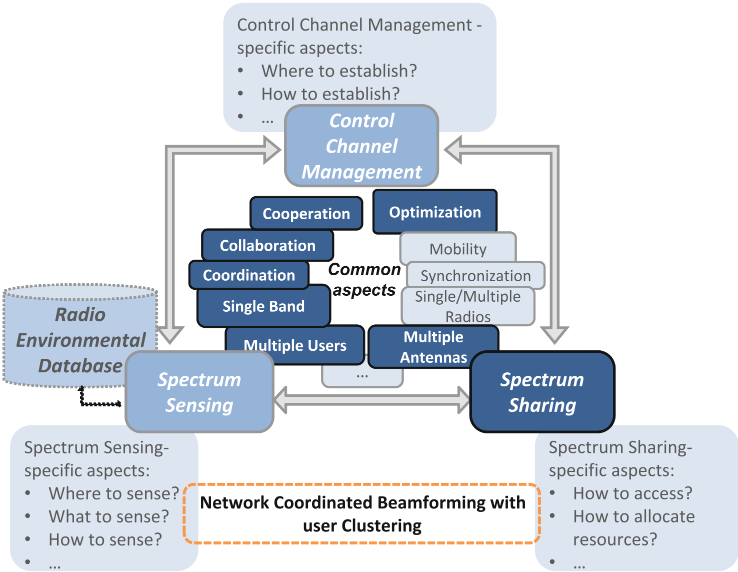

Fig. 4.8 SDMA based SU-SU sharing C-MAC cycle instantiation

that their coverage area overlaps totally or in some parts. Additionally, every system has one Base Station (BS) and multiple users. The BS serves only one user at a time, and interferes with remaining secondary systems, as shown on Fig. 4.9. This definition of the system model can be mapped onto an indoor scenario where multiple secondary systems, spatially collocated, use the same spectrum availability. An example use-case can be the event where a given TV White Space (TWS) is opportunistically shared by multiple LTE femto cells and IEEE 802.11af Access Points (AP), located in the same object.

Due to the overlapping of the systems, the served users will encounter large inter-system interference. One possible solution for mitigating the interference, thus enabling efficient spectrum sharing, is the SDMA approach, for example the NCBF solution. The following subsection will introduce the NCBC approach as a novel spectrum sharing method and will focus on its features and performance.

4.5.2.2 Network Coordinate Beamforming with User Clustering

The NCBF considers a multi-user MIMO channel where all BSs are equipped with one transmit antenna and all users have N_r receive antennas. As already elaborated, only one user per system is served at a given time, hence the total number of served users at any given moment is equal to number of coexisting systems K. It is assumed that all BSs cooperate ideally to compute the transmit beamforming and receive combining vectors [65]. The channel between all BSs and the kth user is represented

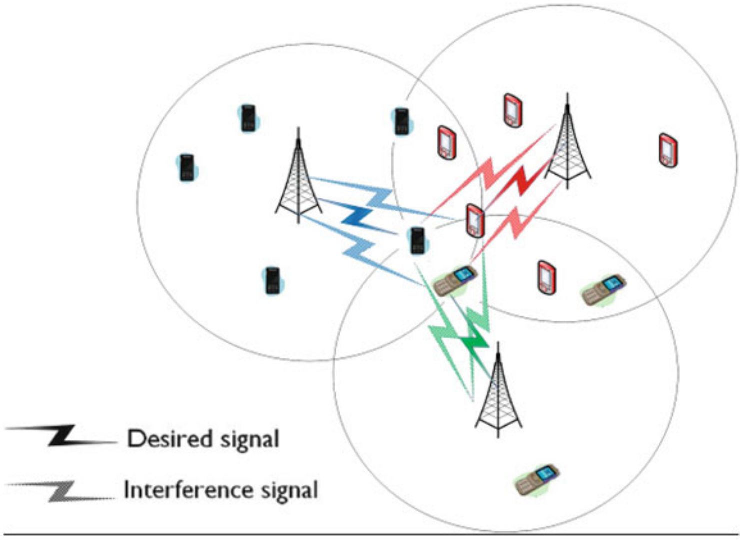

Fig. 4.9 System model example

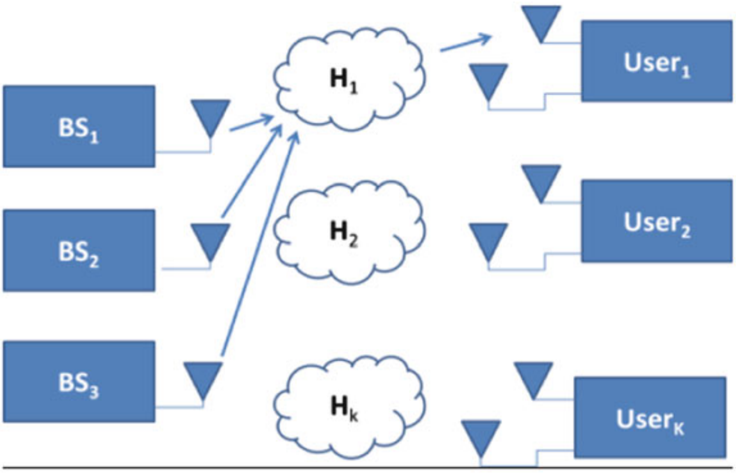

Fig. 4.10 Block diagram of NCBF

by the channel matrix $\mathbf{H}_k$ of size $N_r * K$ and has complex entries for the channel gains. Thus, every column of $\mathbf{H}_k$ represents the single-output multiple-input (SIMO) channel between each BS and the kth user. Figure 4.10 depicts the block diagram example of the NCBF.

The system operates in TDD mode in which the temporal variations of the channels are slow compared to the duration of the data frame [66]. Let x_k and $\mathbf{n}_k$ be the transmit symbol and the noise vector with variance σ_k^2 of the kth user, respectively. Let $\mathbf{m}_k$ denote the transmit beamformer and $\mathbf{w}_k$ denote the receive-combining vector at the kth user. The received signal at the kth user can be expressed as:

$$y_k = \mathbf{w}_k^H \mathbf{H}_k \mathbf{m}_k \sqrt{p_k} x_k + \mathbf{w}_k^H \mathbf{H}_k \sum_{l=1, l \neq k}^{K} \mathbf{m}_l \sqrt{p_l} x_l + \mathbf{w}_k^H \mathbf{n}_k \tag{4.10}$$

where p_k is the allocated transmit power of the BS for the kth user. In the case of coordinated beamforming strategies, the transmitter chooses $\mathbf{m}_k$ such that the subspace spanned by its columns lies in the null space of $\mathbf{w}_k^H \mathbf{H}_k (\forall l \neq k)$, i.e. $\mathbf{w}_k^H \mathbf{H}_k \mathbf{m}_k = 0 (\forall l \neq k)$ and $k = \overline{1, K}$. The authors in [65] have proposed two NCBF algorithms (linear and non-linear approach) that compute the beamforming and receive combining coefficients, which perfectly mitigate the inter-system interference. However, when the number of active users per system is larger than one, the computational complexity of the NCBF increases dramatically making the approach not suitable for real time operation.

The NCBC method decreases the complexity of NCBF by serving a group (i.e. cluster) of users in the given system with the same beamforming coefficients based on the correlation of their channel matrices. For this purpose, every BS has to calculate the correlation of the channel matrices between all of its active users. If the correlation between them is larger than a predefined threshold, they can be served with the same beamforming and receive combining coefficients. This approach can substantially decrease the computational complexity of the legacy NCBF. The correlation between two users can be computed as [65]:

$$\gamma_{corr} = 1 - \|\lambda_k - \lambda_l\|_F \tag{4.11}$$

where λ_k denotes the eigenvalue matrix of the kth user's channel matrix $\mathbf{H}_k$,λ_l denotes the eigenvalue matrix of the kth user's channel matrix $\mathbf{H}_l$ and $\|\cdot\|_F$ denotes the Frobenius norm. If $\gamma_{corr} = 1$, the users will be completely correlated, while for $\gamma_{corr} = 0$, the users will be completely decorrelated. Lower will result in lower system performance and larger inter-system interference. The correlation threshold depends on the required user performance. For example, if the users require high data rate service, than the correlation threshold has to be closer to its maximum value (i.e. $\gamma_{corr} \approx 1$). In case when low delay latency is required (more agile system performance i.e. faster calculation of the beamformers), and the data rate is not crucial, the correlation threshold can attain lower values. The following subsection elaborates on the performance analysis of the proposed NCBC approach.

4.5.2.3 Performance Analysis

This section gives a brief insight into the performance of NCBC in terms of Signal to Interference Ratio (SIR) and the aggregate system capacity. Additionally, it

Table 4.5 Channel model parameters [69]

Channel parameters	
Channel type	NLOS indoor
Delay spread	<100 ns
Number of Paths	8
Bandwidth	10 MHz

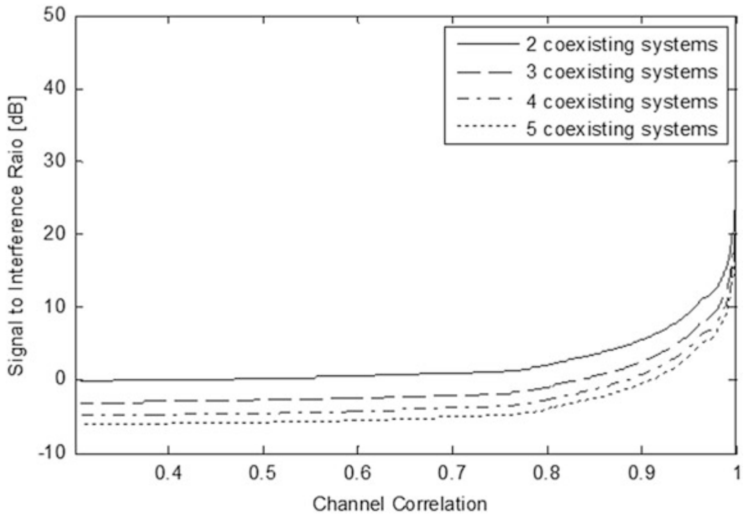

Fig. 4.11 Signal to interference ratio in dependence of the channel correlation

compares the performance of NCBC with a common Frequency Division Multiple Access Spectrum Sharing (FDSS) technique that is based on equal frequency division between all coexisting secondary CR systems. To obtain relevant results, Monte Carlo simulations are carried out for all performance metrics. The channel model used in the simulation analysis is based on the Kronecker MIMO channel model for indoor environments [67] and its parameters are given in Table 4.5. For simplification of the analysis, it is assumed that all BSs use equal allocation of the transmit power for every user, hence denoting $p_k = p$.

The correlation between the channel matrices of the given two users plays a crucial role of the system performance of NCBC. Figure 4.11 depicts the SIR in dependence of γ_{corr} for different number of coexisting secondary CR systems. As seen from the results, the SIR ratio decreases as γ_{corr} decreases, but even for low channel correlation the SIR level does not fall below 5 dB. This SIR level can be satisfactory for a set of different scenarios of modern day wireless systems [68], meaning that in given circumstances it is possible for all users (of a given system) to use the same beamforming and receive combining coefficients. This will drastically decrease the computational complexity of the approach.

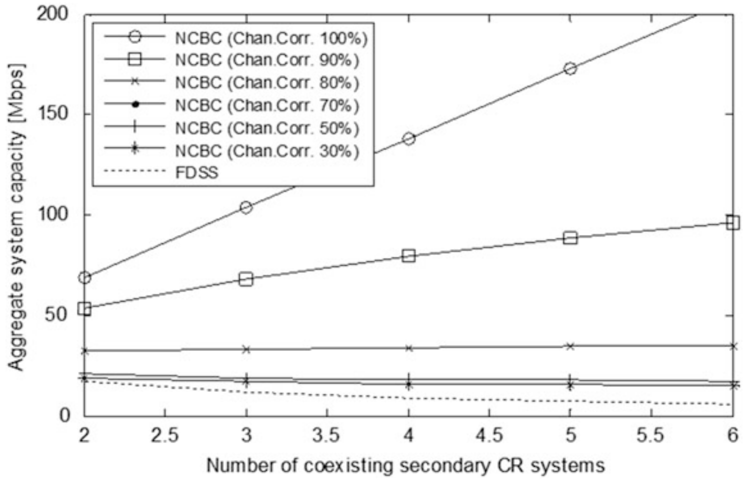

Fig. 4.12 Aggregate system capacity in dependence of the number of coexisting secondary CR systems ($SNR = 10\,\text{dB}$)

The proposed NCBC method is also compared to a simple legacy FDSS method that divides the available spectrum to equal parts in bandwidth, between the coexisting secondary systems. In this manner, FDSS attains equal sharing, i.e. fairness between all coexisting systems.

Figure 4.12 depicts the aggregate system capacity in dependence on the number of coexisting secondary CR systems for both methods. NCBC outperforms FDSS for any case and the performance gain increases as the number of coexisting system increases. This is due to the fact that the spectral efficiency of any CBF scheme rises as the number of transmit and receive antennas increases. In the case of NCBC, the number of transmit antennas is mapped onto the number of BSs, i.e. number of coexisting systems K. For the FDSS scheme the system capacity decreases because the method splits the available spectrum into equal chunks of bandwidth for every coexisting system, thus resulting in decreased system capacity.

The subsection presented a particular spectrum sharing C-MAC cycle use case, denoted as NCBC, which utilizes the aspects of SDMA (i.e. NCFB) and user clustering. The NCBC represents a fundamental routine of the C-MAC protocol, which facilitates the *multiple access* scheme in CR systems. Regarding the common aspects and the operation of the C-MAC cycle, the C-MAC protocol is responsible for aiding the operation of NCBC by collecting and reliably distributing of the beamforming coefficients. Moreover, the C-MAC protocol aids the clustering i.e. grouping of the CR nodes, which is tightly related to the channel correlation coefficient i.e. the required user and system performance (i.e. QoS demands, real-time system operation, etc.), which were previously discussed.

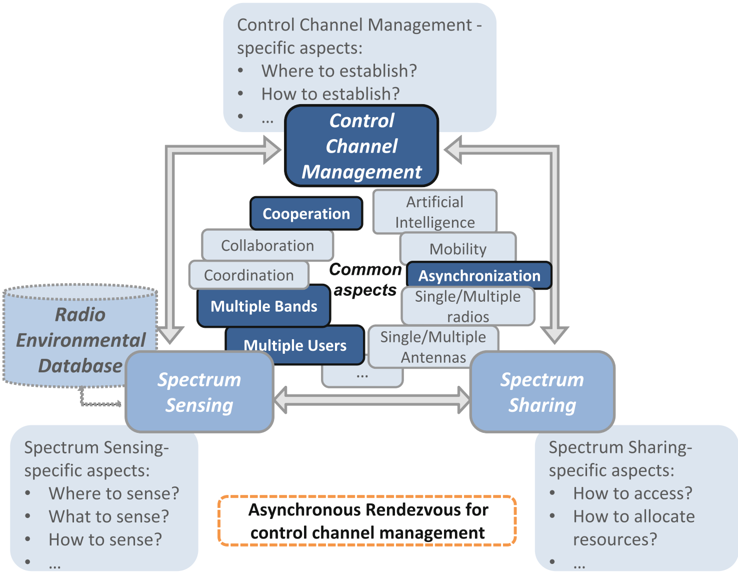

Fig. 4.13 Asynchronous rendezvous CC management C-MAC cycle instantiation

4.5.3 Asynchronous Rendezvous for Control Channel Management

The DCC in multichannel CRNs facilitates the coordination, cooperation and collaboration between the spectrum sensing and the spectrum sharing of the involved CR entities. In particular, the DCC enables the neighbor discovery and control signaling in terms of exchange of spectrum measurement results, access/sharing decisions and feedback etc. However, the existence of dedicated channel for control data exchange in CRNs, especially in distributed environments, may not be always feasible. The DCC needs to be established on a vacant legacy channel accessible by the majority of CR nodes and not interrupted over a longer time period. Aiming to fulfill these requirements the CRs might encounter problems such as spectrum heterogeneity, saturation and single point of failure. In distributed environments, the asynchronous operation of the CR nodes might raise additional reliability and sustainability concerns.

This subsection targets the dynamic control channels, and in particular focuses on a rendezvous protocol for dynamic and asynchronous CC establishment, pinpointed as the most reliable and efficient in terms of the CRs operation, and most harmless and transparent for the primary user operation [51]. Figure 4.13 illustrates the C-MAC cycle instantiation for the rendezvous specific CC management. Namely, the rendezvous protocols operate in multi-band and multi-user environments, and require cooperation between the operating CR nodes in the search of a common vacant legacy channel to rendezvous and exchange the control traffic. Furthermore,

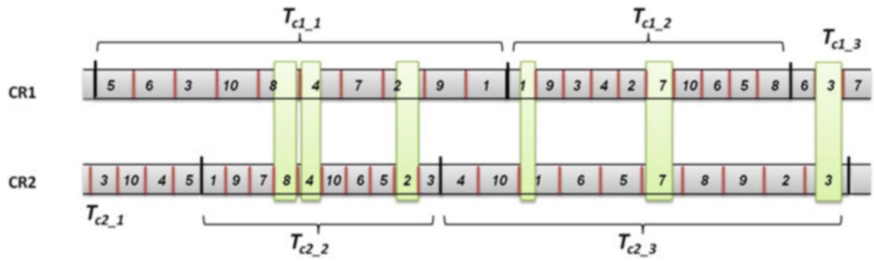

Fig. 4.14 The random rendezvous cycle duration and asynchronous operation provides overlapping between the both cognitive radios in the free channels ($ch_i, i = 1, \ldots, 10$)

the rendezvous control channels can enable, as well as exploit the asynchronous operation of the nodes to provide a faster rendezvous and control channel establishment.

The subsection focuses on a specific rendezvous protocol realization, i.e. the RAC^{2}E-gQS protocol for asynchronous rendezvous in cognitive radio ad-hoc networks. RAC^{2}E-gQS combines the asynchronous and randomness properties of the RAC^{2}E protocol and grid-quorum systems (gQS) to handle the channel heterogeneity and assure more rapid rendezvous. The remainder of the subsection is organized as follows. First, the details on the RAC^{2}E protocol operation are provided, followed by the explanation on the grid-quorum strategies for channel prioritization and mapping. At the end, the subsection provides the performance evaluation of the combined RAC^{2}E-gQS protocol and the concluding remarks.

4.5.3.1 RAC^{2}E Protocol

RAC^{2}E (Rendezvous protocol for Asynchronous Cognitive radios in Cooperative environments [70]) is a rendezvous protocol for distributed cognitive radio network environments. The protocol relies on an asynchronous operation of the nodes, eliminating the need of synchronization establishment, which is an especially difficult task in distributed environments. Moreover, RAC^{2}E fosters even an additional randomization among the nodes to ensure rapid rendezvous on a particular temporary unused channel from the primary system.

The operation of the rendezvous phase of the RAC^{2}E is illustrated on Fig. 4.14. Each cognitive radio aiming to establish a control channel independently selects a random rendezvous cycle duration of $T_{c\_i\_j}$ (ith cognitive radio, jth rendezvous cycle). This time duration is selected randomly with a uniform distribution in the range $[T_{min}, T_{max}]$, where $T_{min} = T_c \Delta T/2$, $T_{max} = T_c \Delta T/2$ and T_c represents the mean rendezvous cycle duration, while $\Delta T = kT_c$ is the randomization interval and k represents the randomization coefficient. The chosen $T_{c\_i\_j}$ interval is further segmented into M time slots, with each slot (having a duration of $\tau_{i\_j} = T_{c\_i\_j}/N$) assigned to a particular channel unoccupied by the primary users. As illustrated

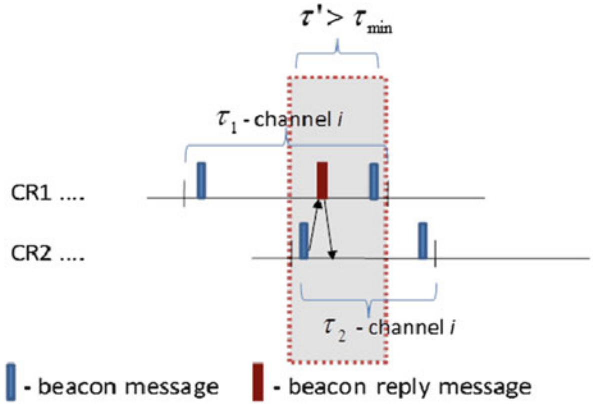

Fig. 4.15 Rendezvous at channel *i* event

on Fig. 4.14, the randomization ensures that overlapping at same channels occurs randomly in wider or narrower time intervals.

The CR sends a short beacon message at the beginning and end of every slot τ_{i_j}, to signalize its presence in the channel. These particular times of beaconing are selected since they provide the highest probability of rendezvous between the CR nodes. In the meantime, between the both beacon messages, the rendezvous node aims to capture the beacons coming from the other CRs operating on the same channel. As Fig. 4.15 illustrates, the randomization (i.e. asynchronous operation of the both nodes) guarantees that at least one of the beacon messages will be delivered to the other nodes tuned to the same channel at the moment. This justifies the preference of a random $T_{c\_i\_j}$ duration (Fig. 4.14), which provides a more successful delivery of the beacon messages, in comparison with the synchronous case. A rendezvous occurs when two nodes are tuned to the same channel and they exchange at least one beacon and one beacon reply message. The condition $\tau > \tau_{min}$ must be fulfilled for the rendezvous to occur, where τ is the overlapping duration and τ_{min} is the required time for exchange and processing of both, the beacon and the beacon reply message (Fig. 4.15).

The mapping of channels into time slots in the rendezvous phase of the RAC^{2}E protocol is another important task. This can be done using several methods considering the channel priorities based on the channel ranking lists created in the sensing phase by each node independently. The combination of the RAC^{2}E protocol with the *grid-quorum based channel mapping* (Sect. 4.5.3.2) can yield a powerful ***RAC^{2}E-gQS rendezvous protocol*** for asynchronous operation in a distributed environment assuring rapid rendezvous between the cognitive nodes.

4.5.3.2 Grid Quorum Channel Mapping

Quorum-based algorithms [71, 72] recently became popular in the area of wireless networking, because of their capabilities to introduce resilience to node and

Table 4.6 4 × 4 grid: Pair-On-Pair (PoP): quorum (0,0) in bold

0	5	11	15
4	1	7	13
10	6	2	9
14	12	8	3

Table 4.7 4 × 4 grid: Diagonal (Diag): quorum (0,0) in bold

0	4	8	12
13	1	5	9
10	14	2	6
7	11	15	3

network failures. There are different types of QSs, within which a grid-based QS proposed by Maekawa [72], is widely utilized in power-saving (PS) protocols. In the grid-quorum systems, sites (elements) are logically organized in a grid in the shape of a square. There are two important properties that a grid-quorum system needs/should satisfy, i.e. the intersection property – the quorums need to intersect when perfectly synchronized, and a rotation closure property – the quorums need to intersect at least once regardless on the elements shifting.

The grid-based QS [56, 73], have recently become a research target in the area of rendezvous protocols, and specifically the channel mapping problems. There are two possible aspects of the grid-quorum systems in terms of the rendezvous protocols: the grid forming scheme and the channel-to-slot mapping scheme. Regarding the grid forming scheme the RAC^{2}E-gQS protocol considers two possible approaches [56, 73]: the Pair-on-Pair (PoP) grid forming and the Grid Diagonal (GD) grid forming, presented in Tables 4.6 and 4.7, respectively. Both schemes satisfy the intersection property, but only the GD scheme satisfies the rotation closure property.

Regarding the channel-to-slot mapping the RAC^{2}E-gQS also considers two approaches [56, 73]: a Row-Column mapping and a Diagonal mapping scheme (illustrated on Fig. 4.16 for the case of four candidate channels). The outcome of both algorithms provides an input to the channel hopping sequences called channel maps. Each node maps its channels according to the channel quality (based on the channel ranking lists formed in the sensing phase) without any exchange of information, where the better channels get priority. The period (cycle) of a channel map depends on the number of channels N and equals $M = N^2$ slots (selected from an NxN grid). Both channel-to-slot mapping methods are designed for three or larger number of channels (i.e. $N > 3$).

Channels are mapped to grid indexes in both methods (channel 1 (C1) is mapped to index 0, channel 2 (C2) to index 1 etc.), where each channel in a CR network has its own index known by the nodes. A node adopts its map according to the priority of the channels, e.g., if a node A has the following map 2/4/3/1, channel C2 is the best, channel C4 is the second best etc. In the first method, the Row-Column mapping, in the first step (Step 1 in Fig. 4.16a), a node selects its channel map in a row-column manner, where the row number (channel number) is always equal to the column number (channel number). The best channel is channel 2, so it selects the quorum slots: 3, 6, 7, 12, 15 (Step 2), channel 3 is allocated to slots 0, 2 and

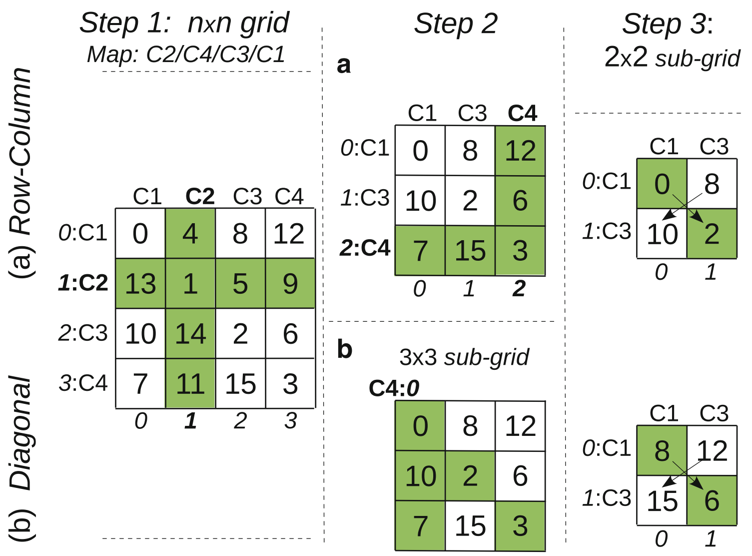

Fig. 4.16 Three steps of the channel-to-slot mapping: (**a**) Row-column, (**b**) Diagonal

channel 1 to slots 8, 10 (Step 3). The second method, Diagonal mapping, is similar to Row-Column mapping until a 3 × 3 sub-grid is obtained. The next channel is mapped (and sub-grid is cut accordingly) in a column-diagonal manner, selecting the first column and the main diagonal, e.g., channel 4 is mapped to slots 2, 3, 7, 10 (Step 2 in Fig. 4.16b). The last two channels are allocated as in the first method.

4.5.3.3 RAC^{2}E-gQS Performance Analysis

This subsection demonstrates the performances of the RAC^{2}E-gQS protocol for the different channel mapping methods elaborated above [56]. The simulation analyses envision a scenario with two cognitive radios aiming for a rendezvous on a certain common channel. Two cases are evaluated:

1. When both CRs have the same channel ranking lists, e.g. both have [1, 2, 3, 4, 5] as a priority list in the case of 5 candidate channels.
2. When the both CRs have completely different channel ranking list, e.g. CR1 has [1, 2, 3, 4, 5] while CR2 has [5, 4, 3, 2, 1] in the case of 5 candidate channels.

These two cases are considered since they provide the two extremes of rendezvous performances, i.e. they are the best and the worst case scenarios. One performance metric of interest in the analysis is the *average number of potential rendezvous (channel matchings)* per cycle which is in inverse proportion to the time-to-rendezvous (TTR). The second evaluated performance metric is the *inter rendezvous time variance*, representing the variance between two potential

Table 4.8 Minimum (Min), maximum (Max) and average (Mean) number of potential RDVs per cycle for gQS schemes in slot synchronized CRNs; No.c/s stands for Number of channels/slots; Ch. Rank. is the channel ranking lists

No.c/s	Ch. Rank.	Metric	PoP^{RC}	GD^{RC}	PoP^{DC}	GD^{DC}
5/25	Same	Min	1	1	3	3
5/25	Same	Mean	6.52	6.52	6.52	6.52
5/25	Same	Max	25	25	25	25
5/25	Different	Min	0	0	0	0
5/25	Different	Mean	3.56	3.56	3.56	3.56
5/25	Different	Max	7	7	7	7
10/100	Same	Min	1	1	3	3
10/100	Same	Mean	13.28	13.28	13.28	13.28
10/100	Same	Max	100	100	100	100
10/100	Different	Min	0	0	0	0
10/100	Different	Mean	6.74	6.74	6.74	6.74
10/100	Different	Max	20	30	28	28
20/400	Same	Min	0	3	0	3
20/400	Same	Mean	26.645	26.645	26.645	26.645
20/400	Same	Max	400	400	400	400
20/400	Different	Min	0	0	0	0
20/400	Different	Mean	13.36	13.36	13.36	13.36
20/400	Different	Max	158	160	108	108

consecutive rendezvous. For the same number of average potential rendezvous per cycle, a higher variance means that channel matchings occur in bursts, leaving longer gaps between bursts, while the lower variance represents the case when channel matchings are more regularly distributed in time. The lower variance case is better since it would assure that two CRs going online would not be stuck into the long no-rendezvous gaps before a successful rendezvous.

Monte Carlo simulations were made to test the performance of the RAC^{2}E-gQS protocol, for 5, 10 and 20 channels. A total of 10,000 trials (rendezvous cycles) were made for each case for statistical correctness. The simulations were performed for a mean rendezvous cycle duration $T_c = 1$ s and duration of $\tau_{min} = 1\,\mu$s. This τ_{min} duration roughly maps to a case when we have 10 Msps sampling rate, 1 byte of beacon and beacon reply message lengths and 4-QAM modulation. Different randomization intervals were evaluated, for $k(k = T_c/\Delta T)$ ranging from 1/4 up to 2 with step size of 1/4.

In order to justify the need of randomization introduced by RAC^{2}E, the grid-quorum channel mapping schemes were tested for a scenario of slot synchronized CRs aiming for rendezvous. Slot shifts are likely to occur since both CRs do not start the rendezvous phases simultaneously. Table 4.8 presents the performances of the grid-quorum schemes in terms of the minimum, the maximum and the average number of potential rendezvous per cycle with respect to the slot shifts. As evident slot shifts can cause high time-to-rendezvous (low avg. number of potential rendezvous per cycle) even in the case when both CRs have the same

Table 4.9 Average number of potential RDVs per cycle for the RAC^{2}E-gQS; No.c/s stands for number of channels/slots; Ch. Rank. refers to channel ranking lists

No.c/s	Ch. Rank.	PoP^{RC}	GD^{RC}	PoP^{DC}	GD^{DC}
5/25	Same	13.042	13.042	13.037	13.043
5/25	Different	7.1065	7.1207	7.0994	7.1045
10/100	Same	26.563	26.557	26.554	26.558
10/100	Different	13.409	13.408	13.434	13.356
20/400	Same	53.263	53.243	53.283	53.325
20/400	Different	26.543	26.424	26.515	26.504

channel ranking lists. The different ranking lists and several slot shifts between can result even in no rendezvous between the CRs.

Table 4.9 presents the average number of potential rendezvous per cycle for the RAC^{2}E-gQS protocol, for the *same channel ranking lists* and *different channel ranking lists* of the CRs. It is evident that the case of same channel ranking lists of the both CRs, results in higher average number of potential rendezvous per cycle than the case with different channel ranking lists. RAC^{2}E improves the rendezvous performances of the grid-quorum channel mapping schemes, as evident comparing Tables 4.8 and 4.9 results. The channel matching percentage, calculated as average number of potential rendezvous per cycle divided by the number of slots, is about 52, 26 and 13.25 % for 5, 10 and 20 number of channels, respectively, for the same channel ranking lists case and two times lower for the case with different channel ranking lists.

All inspected grid-quorum channel mapping methods (PoP-RC, GD-RC, PoP-DC, GD-DC), for the particular channel ranking cases and the particular numbers of available channels, provide the same average number of potential rendezvous per cycle. Although most of the methods experience same (or similar) average number of potential rendezvous per cycle, they differ in the inter rendezvous time variance as demonstrated on Fig. 4.17. It presents the dependence of the variance between consecutive rendezvous with the factor of randomization k, for the cases with same and different channel ranking lists and for 5, 10 and 20 channels. Among the grid quorum strategies, the PoP-DC and GD-DC achieve the lowest variance between rendezvous, for the cases with large number of channels, different channel ranking lists and small number of channels, same ranking lists.

Regarding the randomization factor k, it is evident that there is an optimal setting providing the lowest variance between potential rendezvous. The optimal k depends on the number of available channels, the difference between the channel ranking lists and the employed channel mapping method (Fig. 4.17).

The subsection presented a specific rendezvous protocol for control channel management in dynamic ad-hoc environments, mapped into the C-MAC cycle. The RAC^{2}E-gQS protocol handles and facilitates the asynchronous operation to provide better rendezvous performances. Furthermore, it uses specific grid-quorum systems to handle the channel heterogeneity and provide prioritization for better candidate channels in the rendezvous process. The performance analyses [56] prove

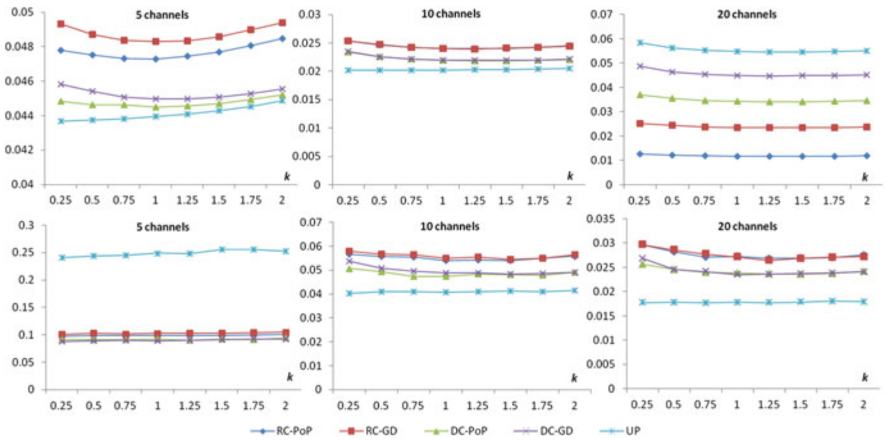

Fig. 4.17 Inter-rendezvous time variance vs. randomization coefficient k, *first row*: same channel ranking case, *second row*: different channel ranking case

the viability of the used grid-quorum schemes for the rendezvous purposes, and the dependence on the randomization introduced by the RAC^{2}E protocol. The results can serve as guidelines for the selection of the most optimal mode of operation of the RAC^{2}E-gQS protocol.

4.6 Concluding Remarks

The Medium Access Control protocols for Cognitive Radio Networks (i.e. the C-MAC protocols) are vital in the process of achieving large spectrum efficiency gain. Utilizing various optimization strategies, the C-MAC protocols strive to maintain the required QoS parameters for the secondary system while providing maximal protection to the primary system. This chapter presented the C-MAC cycle as a generic C-MAC protocol classification and systematization layout, by identifying the spectrum sensing, spectrum sharing and the control channel management as the main generic functionalities. Additionally, the chapter presents brief survey on the state-of-art advances in C-MAC protocol engineering by reviewing existing technical solutions and proposals, identifying their basic characteristics and placing them into the C-MAC cycle layout, with emphasis the C-MAC cycle modularity. It provides overview of large number of technical details concerning the three generic functionalities, (i.e. the radio environmental data acquisition, the spectrum sharing and the control channel management) as the main building blocks of the C-MAC cycle, and related functionality-specific and common aspects. To illustrate the generality of the C-MAC cycle layout, the authors present three C-MAC cycle use cases by mapping a particular C-MAC solution onto a specific generic functionality. These use cases serve as an illustration of the potential benefits of applying the C-MAC cycle on certain C-MAC protocols in terms of understanding the range of applicability of the protocols and their operational limitations.

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