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Non-cooperative and Cooperative Spectrum Sensing in 5G Cognitive Networks

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Contents

Abstract

5G is the expected next step of the mobile cellular network evolution, and it is considered as the answer to the ongoing huge increase of cellular users and services. The architecture envisioned for 5G includes a large number of different network entities and systems that share a common spectrum resource via a dynamic spectrum access (DSA) approach. This solution is expected to significantly increase the overall spectrum efficiency but also introduces the challenge of optimizing the coexistence between the entities forming the overall

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network, by limiting their mutual interference. Within this context, the cognitive radio (CR) paradigm, mainly focusing on its peculiar function, that is, spectrum sensing (SS), is being currently proposed as one of the main enablers for efficient DSA with limited interference. The goal of this chapter is to provide a comparative analysis on CR-inspired spectrum resource management (CR-SRM) mechanisms recently proposed for the 5G architecture, which mainly exploit SS, in order to characterize up-to-date research trends on the topic and highlight still-open challenges and possible future work directions.

Introduction

The rapid increase of cellular devices and services calls for the development of a new generation of the mobile cellular system, and considering the previous generations, the 5G acronym is currently widely adopted for indicating both envisioned requirements and possible solutions. On one hand, three main pillars synthesize the 5G requirements: (a) ubiquitous connectivity, (b) extreme low latency, and (c) very high data rate [1]; on the other hand, three categories identify the possible solutions: (a) massive and heterogeneous network densification, (b) increased bandwidth and spectrum efficiency, and (c) improved energy efficiency [2]. All together, the 5G architecture will include a huge number of different network entities mostly sharing a common spectrum resource, formed by licensed and unlicensed frequency bands, via a *dynamic spectrum access* (DSA) approach rather than traditional, and less efficient, static band assignment; while this solution is expected to significantly increase the overall spectrum efficiency, it also introduces the challenge of optimizing the coexistence between different devices, systems, and technologies.

Within this context, the *cognitive radio* (CR) paradigm and technology, as envisioned in [3], is being currently proposed as one of the main enablers for efficient and dynamic spectrum sharing between 5G network entities. For this reason, in recent years, several *CR*-inspired *spectrum resource management* (CR-SRM) mechanisms have been proposed, at different levels of the 5G architecture, for efficient DSA with limited interference. The key idea of these mechanisms is to exploit the CR capability of obtaining information on the occupation of a spectrum resource and subsequently apply an appropriate action strategy. The function of gathering information on the spectrum resource is usually referred to as *spectrum sensing* (SS); results of spectrum sensing are then used for optimizing the spectrum sharing among network entities.

The goal of this chapter is to provide a comparative analysis on CR-SRM mechanisms recently proposed for the 5G architecture, which mainly exploit SS, in order to characterize up-to-date research trends on the topic and also highlight still-open challenges and possible future work directions.

The rest of the work is organized as follows: section "Towards the 5G Era: Requirements, Enabling Technologies, and the Interference Challenge" introduces 5G basic concepts, first reporting a brief history of the mobile cellular system evolution and then highlighting requirements, most investigated solutions, and one of the main challenges of the incoming generation, that is, the interference management. Section "The Cognitive Radio Paradigm for 5G" frames the topic of this work, providing a brief introduction to DSA and CR paradigms, while also considering the 5G scenarios in which they are envisioned to be applied. Section "CR-Inspired Spectrum Resource Management" is focused on the comparative analysis of recent CR-SRM mechanisms proposed for 5G. Finally, section "Conclusions and Future Work" concludes the chapter and describes open challenges and possible future work.

Towards the 5G Era: Requirements, Enabling Technologies, and the Interference Challenge

Evolution of the Mobile Cellular System

The 5G technology is the next step of the mobile cellular network evolution, and it is globally considered as the answer to the enormous increase of cellular users and cellular-based services. Research communities and industries hypothesize that 5G standards might be introduced in early 2020s. This prediction might confirm the chronological rule of thumb on the development of a new cellular system generation each ten years approximately: the introduction of 1G systems are in fact dated 1982, while the 2G ones were commercially distributed in 1992. 3G systems were then deployed in early 2000s, while 4G systems are being fully exploited since 2010s. Considering the huge amount of users, devices, and systems, the 5G network is expected to have capabilities that significantly overcome the previous system generations, particularly in terms of system capacity, data rate, latency, network reliability and availability, and energy costs and consumption. Many recent reports and projects summarize numerical requirements for the above categories [4–9], and the comparison with the previous generations, in particular with the 4G one, highlights the huge scale of the forecast (see section "5G Requirements" for details). Several proposals are being currently analyzed in terms of solutions and enabling technologies. On one hand, the improved use of existing 3G/4G architectures and systems is considered a good practice, in order to allow interoperability and compatibility; on the other hand, new technological solutions are needed in order to achieve the 5G requirements (see section "5G Enabling Technologies" for details).

5G Requirements

This section highlights the most important 5G requirements, which range from expected data rates to latency indicators, reporting either their absolute values or, when possible, comparative indicators with the 4G assessed performance. References for the reported data are in particular industry reports such as [4–9], among the others.

Massive capacity. In order to deal with the exponential growth of traffic volume, 5G technologies target to increase the overall network capacity, compared with the existing architectures. In particular, when compared to LTE-A, a 100-fold or higher increase of area capacity in Mbit/s per unit area is being targeted.

High connectivity. Compared to LTE-A, a $\geq$ tenfold increase in the number of connected users is expected.

High data rate everywhere. 5G data rate will also significantly increase. In particular, the target of network operators is a $\geq$ tenfold increase in user-experienced throughput (Mbits/s) compared to 4G, aiming at a maximum of 1 Gbps experienced user throughput everywhere, including sparsely populated rural areas. For indoor and dense outdoor environments, a peak data rate exceeding 10 Gbps is expected.

Ultralow latency. Real-time applications, such as tactile Internet, augmented reality, traffic safety, and control of critical infrastructures and industry processes, require much lower latency compared to the 4G performance. 5G is expected to provide an end-to-end latency of about 1 ms or less and almost "zero latency" in case of cloud-based applications.

Improved energy efficiency. This factor is considered extremely important in the 5G context, because it can help in reducing costs and allow energy harvesting, making the network more sustainable. A 100-fold increase of network energy efficiency in bits/Joule is being targeted, together with a ten times prolonged battery life of devices.

Ultrahigh reliability and availability. Besides the above requirements, 5G network should provide connectivity with ultrahigh reliability and availability. In particular, high availability has to be ensured in new mission-critical control services, such as control of critical infrastructures and traffic safety. An availability of 99.999% can be sought in many industrial applications, e.g., energy/smart grid or medical services, to guarantee successful packet delivery within 1 ms. For autonomous vehicles and industrial automation, ultrahigh reliability is expected to be provided with extremely low loss rate.

Table 1 reports a numerical comparison of the main performance indicators between 4G, in particular the LTE-A technology, and 5G, also highlighting the expected order of increase.

Table 1 Comparison of 4G performance and 5G requirements

Performance indicator	4G	5G	Order of increase
Area capacity [Mbits/s/m^2]	0.1	10–100	100–1000
Connection density [devices/km^2]	10^5	10^6–10^7	10–100
User data rate [Mbits/s]	10	100–1000	10–100
Latency [ms]	10	≤ 1	≥ 10
Energy efficiency (bits/Joule)	–	–	100

5G Enabling Technologies

This section highlights the most investigated enabling technologies for the 5G vision. References for the reported solutions are in particular survey papers on 5G such as [1, 2, 10] and [11], among the others.

Network heterogeneous densification. The 5G architecture will be an ultra-dense mixture of network tiers of different sizes and transmit powers, front/backhaul connections, device-to-device (D2D) links, and different radio access technologies (RATs) [12]. Focusing on the cellular network, the coexistence of several classes of base stations (BSs), including macrocells (MBSs) and femto-, pico-, and microcells, generically indicated as small cells (SBSs), will provide improved coverage and spectrum efficiency, if robust mechanisms for interference avoidance are provided. This aspect is analyzed in detail in the following chapter, together with a discussion on cognitive radio-based mechanisms for interference mitigation.

Massive multiple-input multiple-output technology. Massive MIMO, also referred to as large-scale antenna systems, very large MIMO, hyper-MIMO, and full-dimension MIMO and ARGOS, has been recently added to the 5G vision. A massive MIMO system is formed by a BS equipped with a very large number (hundreds to thousands) of colocated or distributed antennas that coherently serves many users within the same time-frequency resource. On one hand, the large number of simultaneously operating antennas can improve significantly the performance in terms of data rate, link reliability, and energy efficiency due to multiplexing and array gains [13, 14]; on the other hand, it increases the hardware complexity while stressing out the need of efficient cooperation between many low-cost low-precision components.

Millimeter-wave communications. The 5G system is expected to work at new, high-frequency bands that are nowadays unused. Among the others, the use of the millimeter-wave (mm-wave) frequency spectrum is of great interest, considering that it exists a vast amount of idle spectrum in the range from 30 to 300 GHz, and preliminary measurements showed that 28 and 38 GHz frequency bands can be used with steerable directional antennas [15]. Issues of using the mm-wave spectrum derive from strong pathloss and atmospheric absorption, low diffraction and penetration around/through obstacles, strong phase noise, and high equipment costs.

Full-duplex communications. Thanks to recent advances in interference cancelation techniques and digital baseband technologies, a full-duplex (FD) transceiver is nowadays capable of transmitting and receiving signals on the same frequency at the same time, thus solving the old days issue of simultaneous Tx/Rx due to high self-interference [16]. FD systems are envisioned to be applied to 5G, thus furtherly increasing the spectrum efficiency. However, several complex types of interference are also introduced, for example, in a multiuser channel sharing system, besides intra-cell interference (among the users in a

Table 2 5G requirements and enabling technologies

Requirement	Main enabling technologies
Massive capacity and connectivity	Network heterogeneous densification, massive MIMO, mm-wave, C-RAN
High data rate everywhere	Network heterogeneous densification, massive MIMO, mm-wave, full-duplex
Ultralow latency	Full-duplex, C-RAN, D2D
Improved energy efficiency	Energy harvesting, D2D
Ultrahigh reliability and availability	Network heterogeneous densification, C-RAN, WNV

cell), intercell downlink-to-uplink interference, and intercell inter-user uplink-to-downlink interference also appear.

Energy harvesting. Energy harvesting has been recently proposed as a potential enabler for solving the energy efficiency requirement. Among the others, several environmental energy sources (e.g., solar and wind energy) and ambient radio signals (e.g., RF energy harvesting) are being analyzed as possible harvesting solutions [17].

Cloud-based access and wireless network virtualization. Cooperation and network virtualization are promising methodologies to be applied in the 5G system; cloud-based radio access network (C-RAN) and wireless network virtualization (WNV), as examples, make possible (a) a distributed architecture for a single BS and (b) simplified resource sharing among many operators, respectively [11]. Several advantages and challenges are being investigated in C-RAN and WNV, as summarized in [18] and [19], respectively.

Table 2 summarizes the above technologies, matching them with the 5G requirements.

The 5G Interference Challenge

In order to highlight the challenge regarding the interference among the heterogeneous 5G network entities, this section introduces in detail the architecture envisioned for the 5G system, first focusing on the cellular network (section "The 5G Cellular Network") and then moving on the more general view of 5G as network of networks (section "5G as Network of Networks"). Definitions of interference at various levels of the 5G architecture are consequently provided and discussed.

The 5G Cellular Network

As briefly introduced in section "5G Enabling Technologies", the cellular part of the overall 5G network will continue the process of *heterogeneous densification* started with the 4G systems. The cellular heterogeneous networks, referred in the following to as *HetNets* or multitier networks, will be the core of the overall 5G architecture:

traditional outdoor MBSs will be massively overlaid with power-limited SBSs, e.g., femtocells, picocells, and microcells (in order to provide a general analysis, this work discusses the interference challenge with the wide concept of small cells. For this reason, the difference between femto-/pico-/microcells is not furtherly highlighted), in space and, possibly, spectrum domains, thus providing an improved network capacity, thanks to (a) a cost-efficient network expansion, in particular for indoor areas [2, 20], and (b) an intelligent traffic balance at each tier via offloading techniques and cell association schemes [21, 22]. Moreover, in a more general view of the network, entities such as relays, operating in a decode-and-forward (DF) mode, and repeaters, working in an amplify-and-forward (AF) mode, will be also developed to increase the coverage area and decrease the power consumption of the network entities [23,24]. It is being proposed that either SBSs or their corresponding users (SUEs) could act as relays for either MBSs or MUEs when needed, thus defining *cooperative* HetNets, in contrast with *noncooperative* ones [25]. While it is clear that MBSs and SBSs will spatially overlay, three main solutions are being proposed for the spectrum domain [26]:

1. **Dedicated-channel**, in which the overall HetNets bandwidth is statically divided in two portions, one dedicated to MBSs/MUEs and the other to SBSs/SUEs.
2. **Partial-channel-sharing**, in which the SBSs/SUEs bandwidth portion is shared with MBSs/MUEs.
3. **Co-channel**, in which the HetNets bandwidth is globally shared between macro- and small cell tiers.

Regarding the HetNets bandwidth, it is assumed that, due to limited availability of the licensed cellular spectrum, it will be formed by both licensed and unlicensed bands, with the latter being free to be used by different systems (e.g., the ISM band). Partial-channel-sharing and co-channel solutions are applicative scenarios of the DSA approach, as will be descripted in section "Dynamic Spectrum Access and Cognitive Radio": in both cases, macro- and small cell tier coexistence is challenging, and the interference arising among them is traditionally referred to as *cross-tier interference* (Cr-TI). Moreover, in all previous spectrum solutions, efficient coexistence between entities within small cell tiers is also a challenge, mainly due to the extremely dense deployment at random locations of SBSs; the interference in this case is referred to as *co-tier interference* (Co-TI). Cr/Co-TI can be seen as particular cases of *intra-network interference* (Intra-NI). In detail, this kind of interference can appear under different forms: the up-/downlink scheduling of macro- and small cell tiers will be in fact asynchronous, and for this reason, if difference between SBSs and SUEs is negligible due to similar locations and transmission powers, intra-NI appears a) from SBSs/SUEs to MBSs, b) from SBSs/SUEs to MUEs, c) from MBSs to SBSs/SUEs, d) from MUEs to SBSs/SUEs, and e) from SBSs/SUEs to SBSs/SUEs [23]. Figure 1 shows the intra-NI scenario in case of downlink transmissions (from MBSs/SBSs to corresponding MUEs/SUEs): intra-NI is indicated as generically affecting the Tx/Rx data link, thus causing interference to both involved transmitter and receiver.

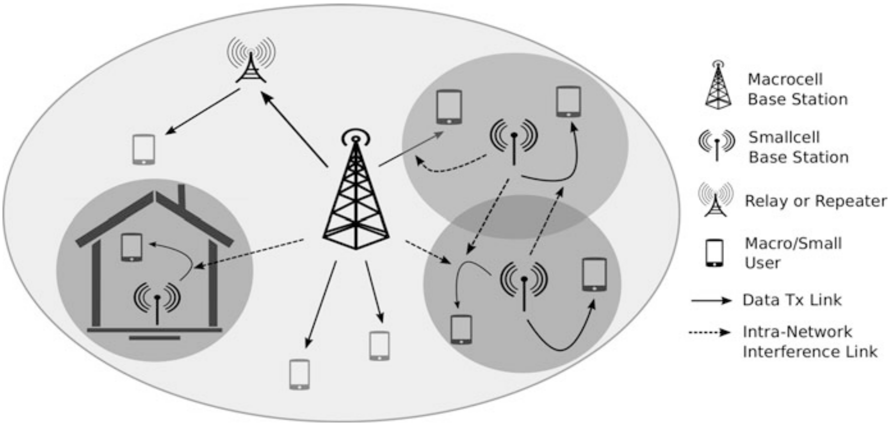

Fig. 1 Representation of HetNets intra-NI scenario in case of downlink transmissions (*straight lines* indicate data links; *dashed lines* indicate intra-NI links)

5G as Network of Networks

As mentioned in section "5G Enabling Technologies", besides the cellular network, the overall 5G architecture will be a mixture of several *radio access technologies* (RATs), allowing the generic 5G user to dynamically connect to different RATs, in order to preserve its required quality of service/experience and the overall network capacity. Among the others, 5G devices will support new 5G standards but also numerous releases of 3G/4G systems, several types of Wi-Fi, and device-to-device (D2D) direct links, all across many spectrum resources [2]. The 5G network will be thus a combination of *multi-RAT HetNets*, and the definition of optimized RAT selection and automatic offloading schemes will be of paramount importance [27].

Within this vision, the use of unlicensed bands opens new opportunities and challenges: some of the RATs will overlay in the spectrum domain (e.g., different releases of Wi-Fi and the small cell tiers, at ISM band and higher frequencies), and these scenarios will require efficient resource management in order to limit the arising *inter-network interference* (inter-NI) [28]. Figure 2 shows the inter-NI scenario in case of downlink transmissions for both cellular network and Wi-Fi and in the presence of D2D communication links: inter-NI is indicated as generically affecting the Tx/Rx data link, thus causing interference to both involved transmitter and receiver.

The Cognitive Radio Paradigm for 5G

In this section, a brief introduction to DSA and CR is provided, in order to highlight general definitions and contributions within this research area, and a focus on SS approaches and techniques is also reported; the application of DSA and CR to the 5G architecture is then discussed.

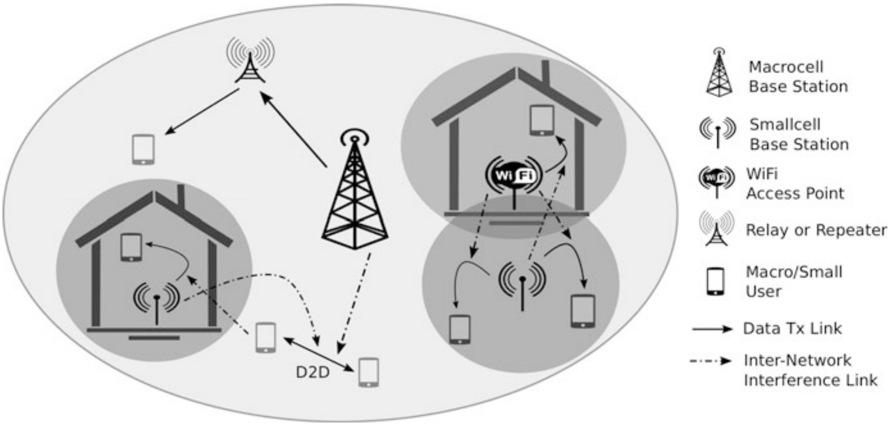

Fig. 2 Representation of multi-RAT HetNets inter-NI scenario in case of downlink transmissions and D2D direct links (*straight lines* indicate data links; *slash-dotted lines* indicate inter-NI links)

Dynamic Spectrum Access and Cognitive Radio

The optimal use of the spectrum resource is an important challenge given the ongoing increase of wireless technologies, systems, and applications. The inefficient spectrum used is largely due to the static assignment of frequency bands to different systems rather than physical shortage, given that, as suggested by several measurements campaigns, many portions of the licensed spectrum are not used either for significant periods of time or in specific geographical areas by the incumbent systems [29, 30]. The need of reforming the spectrum usage has stimulated several activities in the engineering, economics, and regulation communities, having the common goal of optimizing the use of spectrum resources, allowing their use to new services and systems, without damaging the existing ones.

The term dynamic spectrum access is generally used to encompass various approaches to the spectrum reform. According to taxonomy and definitions in [31], DSA approaches can be roughly divided in three main categories:

1. **Dynamic exclusive use model**, in which the static and licensed spectrum assignment is saved but flexibility is introduced in the form of different solutions such as spectrum trading, leasing, and short-time agreement between licensed and unlicensed systems [32].
2. **Hierarchical access model**, mostly applied in case of a licensed band to be shared between licensed primary users (PUs) and unlicensed secondary users (SUs), with the goal of letting the SUs access to the band by exploiting its possible underutilization, while limiting the interference to the PUs [33]. The modalities of the SU spectrum access furtherly identify three sharing scenarios within this model: (a) *underlay* spectrum access, in which the interference between PUs and SUs is controlled by limiting the SUs transmission power;

(b) *overlay* spectrum access, also known as *opportunistic* access, in which the SUs are allowed to transmit full power if they are able to discover, within the licensed band, portions temporarily PU-free; and (c) *hybrid* spectrum access, which combines overlay and underlay access in order to increase the sharing efficiency [34].

3. **Open sharing model**, in which, inspired by the huge success of wireless services operating at unlicensed bands (e.g., the ISM band), different systems openly share the spectrum resource by adopting efficient, either centralized or distributed spectrum sharing mechanisms, with the latter including solutions with roots in game, graphs, and optimization theories [35].

Software-defined radio (SDR) and CR paradigms find a basic application scenario within the DSA context, particularly for hierarchical access and open sharing models. While SDR has been defined as a software-reconfigurable, multi-band device supporting multiple interfaces and protocols, CR, built upon SDR, has been introduced as a context-aware intelligent radio, capable of autonomous reconfiguration by learning from and adapting to the communication environment [3]. The theoretical CR exploits the spectrum resource, by adapting its behavior to the environment, while also considering the requirements of the specific user. Moreover, it is able to learn from past situations in order to always provide the best possible configuration. CR actions are typically scheduled in the so-called cognitive cycle: (a) observe the surrounding environment, (b) plan possible action strategies, (c) decide the optimal operative strategy, (d) learn from experience and derive new action strategies, and (e) act by applying the selected strategy.

While theoretical CR could process an extremely wide range of contextual information, including audiovisual and spatial inputs, CR-related research has been traditionally focused on analyzing and deriving information on the spectrum resource, limiting the contextual information to the one obtained by observing the spectrum domain. In this case, as introduced above, the main function of CRs is spectrum sensing and the cognitive cycle can be simplified in four steps [34], reported in Table 3.

Table 3 The cognitive cycle

Phase	Description
Spectrum sensing	The CRs observe the targeted spectrum resource, thus detecting the traffic activities of noncognitive users and highlighting possible transmission opportunities
Spectrum decision	Depending on the SS results, the CRs plan and decide the action strategy in terms of several functions, e.g., the selection of the best spectrum opportunity, modulation type, and transmission power
Spectrum sharing	The strategy for accessing the spectrum opportunity is applied among all CRs requiring to transmit
Spectrum mobility	The CRs modify their action strategies if a noncognitive user changes its behavior within the spectrum opportunities

The design of a CR network results of paramount importance in all DSA scenarios where different entities and/or networks share the same spectrum resource and therefore could mutually interfere [36]. From the perspective of a hierarchical access model, for example, the SUs should undoubtedly synthesize a CR network while the PUs might be traditional devices: on one hand, in the underlay mode, the SUs can sense the PU activities, estimate the current interference from/to the PUs, and adapt, if necessary, their transmission features, in order to minimize the interference; on the other hand, in the overlay mode, the SUs try to discover via SS, on the overall band, spectrum opportunities free from PUs, and opportunistically use them, until one or more PUs reappear.

The Spectrum Sensing Function

Spectrum sensing plays a fundamental role toward the success of the CR paradigm in terms of spectrum efficiency and coexistence capability, and its definition closely follows the definition of spectrum opportunity. For example, by defining the spectrum opportunity as a band of frequencies that are not being used by the licensed PU at a particular time and/or in a particular geographical area, it immediately arises that SS at least involves frequency, time, and space domains. There are several other dimensions that are possible to explore in order to define and find a spectrum opportunity, e.g., the code and signal propagation direction. On one hand, it is important to define an SS acting across many domains; on the other hand, this requires increased computational complexity and costs for developing and managing the SS function [37].

When focusing on traditional frequency/time/space SS, several definitions can be provided, each one related to a particular highlighted feature [37, 38]. Considering the size of the spectrum resource of interest, SS can be classified into *wideband* and *narrowband* SS: in the first case, the goal is the detection of spectrum opportunities as portions of the overall resource, while, in the second case, the SS is focused on a single portion. Wideband and narrowband SS are usually operated jointly, assuming an intermediate phase in which the sensing device decides a single opportunity where narrowband SS should be applied, among several opportunities previously discovered with wideband SS. In terms of device architecture, SS can be performed in *single radio* and *dual radio*: in the single radio case, specific time allocation for SS is assumed, thus leading to performance of detection and spectrum efficiency depending on the sensing time duration; in the dual radio case, one Tx/Rx chain is dedicated to data transmission/reception, while another chain is dedicated to SS. In this case, SS is also referred to as spectrum monitoring, and performance is improved at the cost of increased hardware complexity and power consumption. The previous definitions assume that the sensing devices are also the ones asking for data transmission such as the SUs in a hierarchical access model. This approach is referred to as *internal* SS, in contrast with *external* SS, where the presence of external network agents, dedicated to SS and able to broadcast the results to the communication devices, is assumed. External SS can solve some problems related to internal SS, such as spectrum and power efficiency, but it introduces new challenges because of the need of exchanging the sensing results on a dedicated control channel. This challenge arises in general when cooperation between sensing devices, in both internal and external SS configurations, is introduced. In fact, in contrast to *local* SS (LSS), in which each device takes independent decisions on the spectrum status, a *cooperative* SS (CSS) approach can be defined, in which the devices share their decisions in order to improve the overall accuracy of SS. Decisions can be shared either with a central unit, also named fusion center, thus defining *centralized* CSS, or among all neighboring devices, referred to as *distributed* CSS. Cooperation leads in general to SS performance improvement, but this depends on the control channel reliability, the type and the fusion rules of shared information, and the number of involved devices; the trade-off between SS accuracy improvement, on one hand, and architecture complexity and overhead due to control message exchange, on the other, have to be considered while designing CSS algorithms [39].

Besides the above definitions, a plethora of SS techniques, approaches, and methodologies, together with challenges and issues, can be highlighted. Providing a survey on SS is out of the scope of this chapter and the interested reader can refer to [37, 38, 40], among the others, for detailed and complete reviews. However, observing that CR devices do not in general interact with noncognitive users to verify their presence, indirect detection sensing techniques for (a) *transmitter*, (b) *receiver*, and (c) *interference temperature* detection have been introduced in recent years. The first case is the most investigated one, and the corresponding techniques, ranging from traditional energy and feature detectors to recent wavelet transform-based, statistical and sub-Nyquist approaches, differ each other depending on the a priori knowledge on the device to be detected and the accuracy/complexity trade-off. Complexity and adaptability of the SS technique to different environments play a fundamental role in the 5G context, considering the high number of possible scenarios of interference, and the level of heterogeneity expected for and required by the 5G architecture, as already reported in section "5G Enabling Technologies".

CR-Inspired Spectrum Resource Management

In this section, the state of the art of CR-SRM mechanisms proposed for the 5G architecture is reported and analyzed, first focusing on the HetNets case and then moving on the more general multi-RAT HetNets one.

Focus on HetNets

Focusing on the HetNets forming the cellular network, the application of CR capabilities depends on the possible HetNets usage scenarios. On one hand, with reference to noncooperative HetNets, the scenario in which cognitive small cell tiers provide support to the macrocell tiers while acting on the same spectrum resource is particularly analyzed in recent literature, and it is also actively pursued by the industry; on the other hand, in case of cooperative HetNets, the scenario suggesting the presence of cognitive relays/repeaters, capable of autonomously selecting the optimal relying/amplifying strategy for further cellular coverage enhancement, is of particular interest. Since centralized control for both spectrum access and intra-NI mitigation is hard to implement, because of scalability of control message exchange among and within tiers [41], CR-SRM mechanisms in the form of cognitive DSA are highly desirable, also considering that the DSA hierarchical access model perfectly matches the HetNets scenarios of partial-channel sharing and co-channel deployment, with macrocells and small cell tiers having the role of PUs and cognitive SUs, respectively.

Solutions Based on Local Spectrum Sensing

Within this context, SS is mainly adopted for a direct analysis of the spectrum resource, in order to estimate and mitigate the intra-NI. Focusing on Cr-TI, several approaches might be used for making possible an efficient spectrum access to low-priority small cell tiers: on one hand, considering an overlay access scenario, interference from/to MBSs/MUEs might be avoided through direct SS by SBSs/SUEs [21]; on the other hand, considering an underlay access scenario, SS-based mechanisms might be used to estimate the interference from/to MBSs/MUEs within the targeted spectrum resource. More complex hybrid access might be also considered: in [23], for example, when considering SBSs/SUEs and MBSs/MUEs spatially overlapped, overlay access is proposed on the spectrum opportunities, while underlay access is carried out on spectrum portions being used by MBSs/MUEs covering different geographical areas, after estimating, through SS-based mechanisms, the possible interference caused to them.

Focusing on Co-TI, several different approaches can be highlighted. On one hand, SBSs/SUEs access might be regulated via SS-based access schemes, as proposed in [21], where Aloha-like access vs. SS-based CSMA have been comparatively evaluated; on the other hand, the recent trend seems to prefer solutions based on game theory [42] and optimization methods [43, 44], with a particular emphasis on maximizing the small cell throughput.

Cr-TI and Co-TI are mostly analyzed in conjunction and, also in this case, SS mechanisms are used in particular for Cr-TI mitigation, while game and optimization theories are preferred for Co-TI [26, 28]. Furthermore, it can be highlighted that the reuse of existing 4G functionalities is being widely analyzed for 5G SS mechanisms: in [26], each SBS mitigates Cr-TI by comparing the gathered information on macrocell scheduled transmission activities, broadcasted by the MBSs in a common dedicated signaling channel, with the SS measurements of the received interference power, which is an indicator already adopted as a sensing quantity in LTE-A tiers. Besides the received interference power, reference signal received quality and number of neighboring cells are the others 4G indicators to be possibly used in 5G interference scenarios, as analyzed in [28]; Cr-TI mitigation is here achieved by also introducing a first step of cooperation within the small cell tier: while the SBS measures the received interference power, thus obtaining a global tier interference indicator, the SUEs measure their own reference signal received quality, thus obtaining a local interference indicator. The SUE measurements are then reported to the SBS, which decides on the spectrum resource occupancy, by applying a compressed sensing approach for overcoming the possible huge amount of received data.

Solutions Based on Cooperative Spectrum Sensing

While in [28] a centralized CSS scheme has been suggested for Cr-TI mitigation only, both centralized and distributed CSS approaches are being proposed for global intra-NI interference mitigation. Within this context, one of the main challenges is the energy efficiency, to be achieved by minimizing SS efforts and control message exchange. For this reason, when considering centralized CSS, a sequential SS algorithm with hibernation state for the sensing devices has been proposed in [45], while external CSS architecture with dedicated network entities referred to as spectrum agents (SAs) has been recently discussed in [46]. Even in this case, mechanisms for energy efficiency are highlighted: the SAs are in fact supposed to be activated through an explicit sensing request either by the SBS/SUE needed to transmit or by a central unit that is also in charge of the final decision on the resource occupancy. Figures 3 and 4 graphically clarify some of the concepts being discussed; on one hand, Fig. 3 reports a representation of three different internal SS mechanisms that are local SS, centralized CSS, and distributed CSS: considering the downlink scenario, it is assumed that, in all cases, the SBS activates the SS function in order to transmit data to the SUEs, and in case of centralized CSS, it also acts as central unit. On the other hand, Fig. 4 reports two simplified scenarios of external and centralized CSS: in this case, considering again the downlink scenario, it is assumed that, the SBS needed to transmit activates the SAs, they apply SS and report the results either to the SBS or to a dedicated central unit. It is worth noting that the cases reported in both Figs. 3 and 4 consider the execution of SS within an isolated small cell tier: approaches considering possible cooperation between near/overlapping small cell tiers can be also taken into account.

Considering that the reliability of the common control channel is another factor significantly affecting the CSS performance, an MAC protocol with dynamic common control channel selection has been recently proposed in [47], referred to as DCCC-MAC, and formed by four phases: (a) CSS by the SUEs on the channels forming the spectrum resource, (b) selection by the SBS of a common control channel among the channels sensed as free from macrocell activities, (c) contention-free allocation and data transmission of the cooperative SUEs on the other channels detected as free, and (d) beaconing for synchronization purposes within the cell.

In the context of distributed CSS, joint optimization of sensing parameters, transmission powers, and spectrum resource allocation has been discussed in [48], where an optimal trade-off between the power spent for transmission and the power spent for sensing is also derived. CSS has been also proposed in the hypothesis of mobile PUs, which mainly matches the HetNets uplink scenario (MUE/SUE transmitting to corresponding MBS/SBS), for joint estimation of spectrum occupancy and spatial localization of MUEs [49].

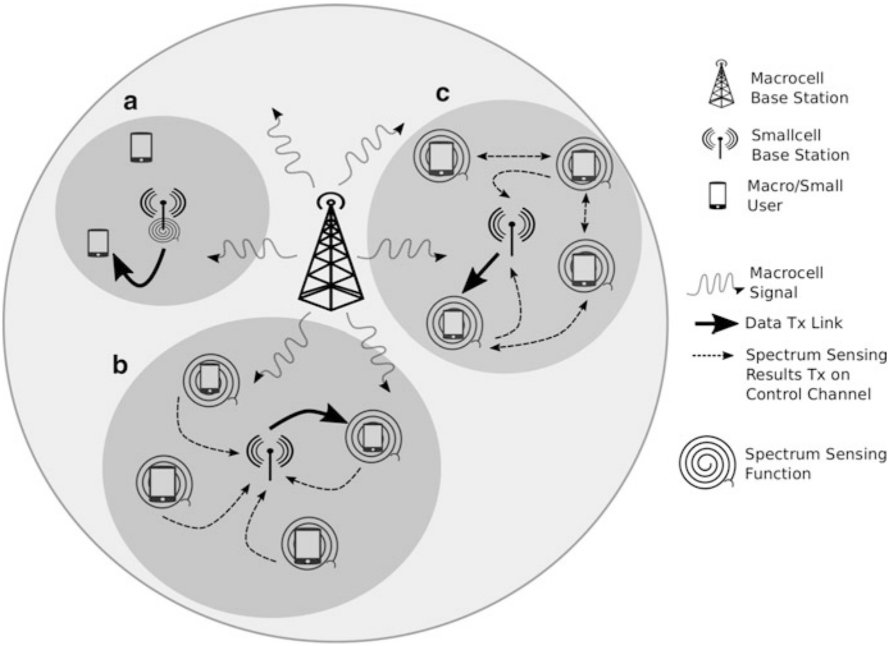

Fig. 3 Representation of three internal SS scenarios, in case of downlink transmissions: (**a**) local SS by the SBS; (**b**) centralized CSS, the SUEs, activated by the SBS, apply SS and report their results to the SBS that also acts as central unit; (**c**) distributed CSS, the SUEs, activated by the SBS, apply SS and forward their results to the nearest neighbors

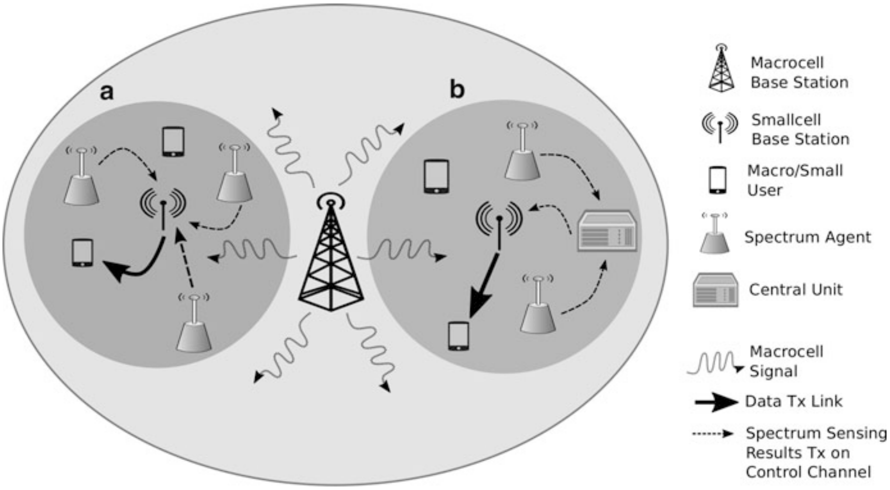

Fig. 4 Representation of two external SS scenarios, in case of downlink transmissions: (**a**) centralized SS mode 1, the SBS activates the SAs and acts as control unit; (**b**) centralized SS mode 2, the SBS activates the SAs and receives the final SS decision from a dedicated central unit

Imperfect Spectrum Sensing

The imperfection of SS due to possible miss-detections and false alarms is a nontrivial problem that significantly affects the expected network performance. It recently started to be explicitly considered in the HetNets design and spectrum allocation schemes: on one hand, the spectrum allocation framework proposed in [50, 51] for OFDMA small cells considers both constraints deriving from intra-NI and SS errors on the channels forming the spectrum resource; on the other hand, the problem deriving from possible SS low reliability can be mitigated by limiting its use within a more sophisticated sharing mechanism, as suggested in [52], where a centralized spectrum sharing has been proposed: distributed SS is executed by SUEs, and results are reported to the nearest SBS. However, the SS results are only used by MBSs/SBSs as side information, and the final spectrum sharing decisions are mainly based on the policies defined by a centralized controller.

Energy Efficiency

Spectrum efficiency and interference mitigation issues are mostly analyzed in conjunction with many other challenges deriving from 5G requirements. As already observed in section "Solutions Based on Cooperative Spectrum Sensing", one of the most investigated combinations is with energy efficiency and harvesting, considering their paramount importance for the creation of 5G devices and infrastructures [25]. When considering CR-SRM mechanisms, energy efficiency of spectrum sensing and sharing assumes primary importance: it has been demonstrated that the energy consumption of energy detector SS with off-the-shelf components is nearly twice the one of a normal transmission state, and for this reason, the constraint on the power consumption has to be considered in the SS time duration optimization [53]. Moreover, in the context of HetNets, energy-efficient SBS/SUE spectrum sharing is being investigated: once a spectrum opportunity has been discovered, the optimization of the SBS/SUE transmission power can be achieved by considering that the highest its value, the highest the possible intra-NI and power consumption [53].

Energy harvesting is also highlighted in the 5G HetNets scenarios: different network entities can be empowered by different energy harvesting solutions, and CSS mechanisms for discovering spectrum opportunities should take this aspect into account in order to adaptively selecting the optimal number of cooperative neighbors and the energy that can be consumed by each one in the SS phase. In [54] an MAC protocol synthesizing these aspects, divided into contention, sensing, and transmission phases, has been proposed and analyzed.

Focus on Multi-RAT HetNets

As discussed in section "The 5G Cellular Network", the HetNets architecture is interference-affected, given that macro- and small cell tiers share the licensed spectrum. Even if the CR-SRM mechanisms discussed in section "Focus on

HetNets" could mitigate this interference, the large-scale deployment of small cells is posing an increasing challenge. For this reason, research communities and industries are discussing on the utilization of other spectrum resources for small cells, including unlicensed spectrum bands, such as the 2.4 and 5 GHz bands that Wi-Fi systems operate in [55].

Within the 4G context, tentatives of exploring the unlicensed spectrum currently used by Wi-Fi systems for LTE/LTE-A systems are mainly known as LTE-unlicensed (LTE-U) or licensed-assisted access using LTE (LAA-LTE) and clearly pose an initial inter-NI issue to be managed between the cellular network and the Wi-Fi systems; when considering 5G networks, the coexistence of HetNets and Wi-Fi becomes even more challenging and requires in-depth research, considering the increasing number of overall network scenarios and entities. As an example, the same systems are also possibly interfering at the 60 GHz mm-wave bands, where the new IEEE 802.11ad standard, also known as WiGig, is about to work, and on parallel, 5G small cell SBSs/core network backhaul links are being envisioned, given that wired and in-band wireless links may not perform well because of the dense deployment of small cells [56].

Nowadays, considering their huge proliferation, Wi-Fi systems are mainly playing an important role in offloading traffic from the heavily loaded cellular network, especially in indoor traffic hotspots and in poor cellular coverage areas, and the huge amount of recent work on the topic proves that efficient offloading schemes and intelligent RAT selection are fundamental tools in achieving satisfactory network performance, if inter-NI mitigation is provided [57].

HetNets vs. Wi-Fi: Inter-NI Mitigation

HetNets and Wi-Fi coexistence can be envisioned to be cooperative or otherwise; considering that the first case implies modification of existing protocols due to the need of control message exchange, most of the work has been nowadays focused on noncooperative RATs, thus proposing CR-based solutions.

Resource partitioning between HetNets and Wi-Fi are being discussed: while unlicensed spectrum partitioning guarantees fairness between small cells and Wi-Fi but suboptimal spectrum efficiency [58], time-domain dynamic resource sharing, based on the almost blank subframe (ABSs) mechanism, is expected to be a more efficient solution. In the context of LTE/Wi-Fi coexistence, the ABSs, which are subframes with reduced power and data, are randomly transmitted by the LTE network, without coordination with the Wi-Fi system; the Wi-Fi access points can detect the ABSs (via CSMA/CA or SS) and use them for their own transmissions. It has been shown that this mechanism sets a reasonable trade-off between the Wi-Fi and the LTE throughput performance [59,60]. Moreover, interference avoidance can be obtained, as previously discussed in section "Solutions Based on Local Spectrum Sensing", by adopting 4G SS indicators [28] and estimating the density of nearby Wi-Fi transmissions [60]. Coexistence at the 60 GHz mm-wave has been recently investigated in [61], where wavelet transform-based SS and filter bank multicarrier modulation techniques have been proposed to increase the small cell tier throughput.

Conclusions and Future Work

This chapter has presented a comparative analysis of recent CR-SRM mechanisms proposed in literature for the incoming 5G network and exploiting, in particular, the SS function. After reporting a summary on 5G envisioned requirements and possible enabling technologies, the interference challenge at different levels of the 5G architecture has been discussed, and the application of the CR paradigm, with a particular focus on SS and CSS, has been descripted in light of recent literature. The analysis suggests that CR is being extensively analyzed in the context of 4G/5G multi-RAT HetNets: in particular, when considering the cellular part of the 5G network, SS-based approaches seem to be extremely suitable for Cr-TI mitigation scenarios, where a particular emphasis is being given to cooperative approaches, energy efficiency, and an overall optimal sensing/transmission network organization through specific MAC protocols; when considering the multi-RAT scenarios, SS-based approaches are being proposed for improving the coexistence of different RATs on a common unlicensed spectrum resource, with a particular focus on the optimization of HetNets and Wi-Fi coexistence, given the importance of Wi-Fi, as supporting technology for offloading, in the general 5G vision.

Nowadays, the presented topic is still extremely open and challenging and calls for further research in a broad range of scenarios. For example, most of the work either does not indicate the SS technique to be used or assumes simple energy detector SS schemes. However, the SS technique might be selected with reference to the applicative scenarios: for example, in case of Cr-TI mitigation within the cellular licensed spectrum, it can be assumed that small cell tiers are focused on discovering macrocell activities and thus, knowing their transmission features, more complex and performing SS techniques might be used. In general, specificity of SS should be considered for more detailed performance analysis. Another aspect that might be addressed more in detail is the possible users' mobility, considering that majority of 5G users is assumed to be mobile in the area of interest; this is extremely relevant also for D2D communications and cooperative architectures with relays and repeaters. Finally, full-duplex and massive MIMO might be taken into account in all the above scenarios, given that they are considered as fundamental technologies for a complete success of the 5G era.

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