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Spectrum sharing methods for the coexistence of multiple RF systems: A survey

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ABSTRACT

Due to the explosive growth of wireless devices and wireless traffic, the spectrum scarcity problem is becoming more urgent in numerous Radio Frequency (RF) systems. At the same time, many studies have shown that spectrum resources allocated to various existing RF systems are largely underutilized. As a potential solution to this spectrum scarcity problem, spectrum sharing among multiple, potentially dissimilar RF systems has been proposed. However, such spectrum sharing solutions are challenging to develop due to the lack of efficient coordination schemes and potentially different PHY/MAC properties. In this paper, we investigate existing spectrum sharing methods facilitating coexistence of various RF systems. The cognitive radio technique, which has been the subject of various surveys, constitutes a subset of our wider scope. We study more general coexistence scenarios and methods such as coexistence of communication systems with similar priorities, utilizing similar or different protocols or standards, as well as the coexistence of communication and non-communication systems using the same spectral resources. Finally, we explore open research issues on the spectrum sharing methods as well as potential approaches to resolving these issues.

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1. Introduction

Due to the explosive growth of smartphones and other wireless devices, the amount of wireless traffic has been increasing rapidly. At the same time, the amount of spectrum resources carrying the wireless traffics is almost fixed for most wireless networks. Furthermore, it is almost impossible to allocate more spectrum resources to specific wireless networks due to regulatory constraints. Hence, the spectrum scarcity problem becomes more pronounced in more and more RF systems, e.g., cellular networks [1], vehicular communication networks [2], wireless local area networks (WLANs) [3], radar systems [4] and wireless personal area networks (WPANs) [5]. However, it has been observed that the usage efficiency of large quantities of current spectrum resources is rather low due to fixed spectrum allocation policies. More specifically, spectrum resources of one RF system are not allowed to be utilized by other systems, which results in significant levels of spectrum underutilization. Therefore, a promising method to alleviate the spectrum scarcity problem is to improve spectrum utilization via spectrum sharing among different RF systems. An example is the coexistence of various wireless networks (e.g., Wi-Fi, Zigbee, Bluetooth etc.) in the license-exempt 2.4 GHz industrial, scientific, and medical (ISM) band. However, spectrum sharing among different RF systems is non-trivial because most wireless standards do not explicitly include spectrum sharing provisions, and various wireless networks operating in the same spectrum band may even use significantly different PHY/MAC protocols [6,7]. Furthermore, there are only a very limited number of existing protocols and standards that allow coordination of multiple heterogeneous RF systems. The terminology "spectrum sharing" was introduced over a decade ago [8–10], and various spectrum sharing mechanisms have been extensively studied since then [11–13]. Traditionally, the term "spectrum sharing" means that unlicensed devices (i.e., secondary users) are allowed to utilize a frequency band on the condition that they would not cause harmful interference to licensed devices (i.e., primary users) of that band. Hence, "spectrum sharing" is also termed "cognitive radio" (CR) [14–16], "dynamic spectrum access" (DSA) [17–19], and "opportunistic spectrum access" (OSA) [20–22] technology. CR

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techniques have been extensively studied, and there exist several comprehensive survey papers that summarize historical and state-of-the-art works in this area (e.g., [23–25]). Different from these definitions, in this paper, "spectrum sharing" (or "coexistence") is defined as the general scenario where multiple, potentially different RF systems operate in the same frequency band. In this sense, CR technology is only one of the "spectrum sharing" technologies considered in this paper, which particularly deals with spectrum sharing between a primary system and a secondary system. This paper covers a wider range of potential approaches to improving spectrum usage efficiency in current RF systems.

In this paper, we investigate existing spectrum sharing methods dealing with the coexistence of multiple RF systems in the same frequency band. The contributions of this paper are threefold:

- To the best of our knowledge, this is the first comprehensive survey studying general spectrum sharing methods for the coexistence of multiple RF systems in the same frequency band.
- We classify existing works on spectrum sharing into a number of general spectrum sharing methods and discuss their applications in existing coexistence scenarios.
- We explore open research issues on the spectrum sharing methods and provide potential approaches to resolving these issues.

The remainder of this paper is organized as follows. First, we discuss existing books and survey papers on spectrum sharing methods in Section 2. Then, we present the classification of spectrum sharing methods in Section 3. In Sections 4–6, we discuss spectrum sharing methods dealing with coexistence of homogeneous, heterogeneous, and multiple hybrid networks, respectively. Then, we investigate the coexistence of a communication system and a non-communication system in Section 7. Open research issues on the spectrum sharing methods and potential approaches are discussed in Section 8. The paper is concluded in Section 9.

2. Related works

Before discussing existing books and survey papers on spectrum sharing methods, we first classify them based on the coexistence scenarios they apply to. In this paper, "coexistence scenarios" denote neighboring RF environment (or features of coexisting RF systems) that an RF system is involved in. For example, spectrum sharing between a Wi-Fi network and a ZigBee network is a specific coexistence scenario of two heterogeneous networks. Note that our classification is a generalization of several popular classifications of coexistence scenarios such as those in [29,41,42]. As shown in Fig. 1, coexistence scenarios can be divided into "horizontal" spectrum sharing and "vertical" spectrum sharing cases [29] based on the spectrum access priorities of coexisting RF systems.

Horizontal sharing refers to the scenarios where coexisting systems have the same regulatory status (or priority) over the same frequency band, e.g., the coexistence of Wi-Fi and Bluetooth devices in the license-exempt ISM band. In contrast, vertical sharing refers to the scenarios where coexisting systems have different regulatory status (or priorities) over the same frequency band, e.g., coexistence of licensed and unlicensed devices in the TV white space (TVWS) band. Furthermore, horizontal sharing scenarios can be classified into three categories: coexistence of homogeneous networks, the coexistence of heterogeneous networks, and coexistence of multiple hybrid networks.

Notice that in Fig. 1, "heterogeneous networks" means that all coexisting networks are of different type, e.g., the coexistence of an IEEE 802.22 network, an IEEE 802.11a network, and a cellular network. In contrast, "hybrid networks" means that a network can be the same type as one of the coexisting networks, e.g., the coexistence of multiple IEEE 802.22 networks, multiple IEEE 802.11a networks, and multiple cellular networks. In particular, in the case of coexisting hybrid networks, each network has to consider its coexistence with both multiple homogeneous networks and heterogeneous networks. These three horizontal coexistence scenarios will be discussed in detail in Sections 4–6, respectively.

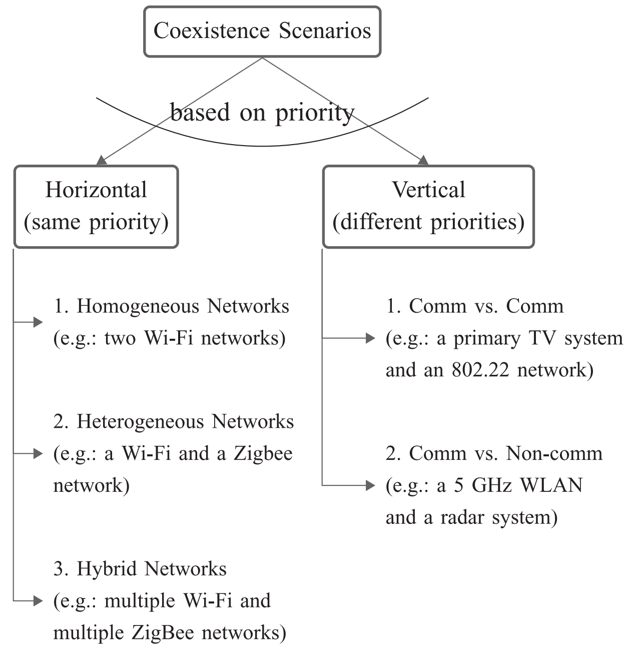

Fig. 1. Classification of coexistence scenarios.

The reasons for the distinction among homogeneous, heterogeneous and hybrid coexistence are as follows. Firstly, most coordinated methods for homogeneous networks usually require information exchange or very explicit coordination of the coexisting networks, which can be impossible for heterogeneous or hybrid networks. For example, the IEEE 802.22 standard includes a self-coexistence mechanism to facilitate the coexistence of multiple 802.22 networks. This mechanism requires the exchange of channel usage information between two coexisting networks, which is explicitly defined in the standard. However, the IEEE 802.22 standard does not include any mechanism for its coexistence with other heterogeneous networks, in which case uncoordinated methods or coordinated methods with no information exchange are preferred. Although some coordinated methods have also been proposed for the coexistence of two heterogeneous networks, they can hardly be implemented in existing standards. This is the main drawback of such methods.

Secondly, most uncoordinated methods for homogeneous coexistence are mostly inapplicable for heterogeneous or hybrid coexistence because they usually assume that the coexisting networks use the same PHY and MAC layer techniques. For example, a CSMA-like contention mechanism can be used to facilitate WLAN–WLAN coexistence or Femtocell–Femtocell coexistence, but it cannot be used to enable WLAN–Femtocell coexistence because of the significantly power level asymmetry of the two networks. More specifically, the WLAN can easily starve the femtocell network due to its significantly higher transmit power.

Thirdly, neither the methods for homogeneous coexistence nor the methods for heterogeneous coexistence can accommodate the hybrid coexistence. Although some methods for heterogeneous coexistence can be used to enable the hybrid coexistence, they neither leverage the fact that some coexisting networks can have the

Table 1
Existing works.

Year	Reference	Scenarios	Band	Networks	Key topics
2003	[26]	Horizontal	ISM	WLAN, WPAN	Two coexistence mechanisms for coordination and coordination-free cases
2005	[27]	Horizontal	ISM	802.11b, Zigbee, 802.15.4	Mutual interference among heterogeneous networks in the ISM band
2006	[24]	Vertical	Licensed	CR secondary networks	CR technology: spectrum sensing/management/mobility/sharing
2011	[28]	Vertical	Licensed	CR secondary networks	CR technology: centralized and distributed spectrum management methods
2011	[25]	Vertical	Licensed	CR secondary networks	CR technology: spectrum sensing and dynamic spectrum allocation
2011	[29]	All	All	WLAN, Wi-Fi, Zigbee, cellular, radar	Background and theory on spectrum sharing, listen-before-talk approach, radio resource management, CR, and four spectrum sharing examples
2012	[30]	Vertical	Licensed	CR secondary networks	CR technology: classification/comparison of CR MAC protocols
2013	[31]	Vertical	Licensed	CR secondary networks	CR technology: machine-learning techniques in CR networks
2013	[32]	Vertical	Licensed	CR secondary networks	CR technology: decision-theoretical solutions for channel selection/access
2013	[33]	Vertical	Licensed	CR secondary networks	CR technology: channel assignment approaches in CR networks
2013	[34]	Vertical	Licensed	CR secondary networks	CR technology: spectrum characterization/selection and CR reconfiguration
2014	[35]	Horizontal	ISM	Wi-Fi, Bluetooth, Zigbee, microwave oven	Coexistence between Zigbee and other networks operating in the 2.4GHz band, existing interference mitigation methods
2014	[36]	Vertical	Licensed	CR secondary networks	CR technology: overview/classification of MAC protocols in CR networks
2014	[37]	Vertical	Licensed	CR secondary networks	CR technology: resource allocation techniques in CR networks
2014	[38]	Vertical	Licensed	Radar, TV, and cellular	CR technology: methods on detecting spectrum opportunities
2015	[39]	Vertical	TVWS	CR secondary networks	CR technology: MAC issues on the access of TV white space
2015	[40]	Vertical	Licensed	CR secondary networks	CR technology: power control and beamforming in CR networks
2015	This one	All	All	All RF systems	Comprehensive survey of spectrum sharing methods and their applications

same PHY/MAC layer features nor overcome the mutual interference between these homogeneous networks. For example, the dynamic channel selection method can facilitate the coexistence of a Bluetooth network and a WLAN. However, it does not directly apply to the coexistence of multiple Bluetooth networks and a WLAN due to the mutual interference among the neighboring Bluetooth networks.

Vertical spectrum sharing is often regarded as an alias of CR technology. As shown in Fig. 1, vertical spectrum sharing can be divided into two categories: coexistence of two communication systems (e.g., coexistence of an IEEE 802.22 network and microphone devices in the TVWS band), and coexistence of a non-communication system and a communication system (e.g., coexistence of a WLAN and a terminal Doppler weather radar system in the 5 GHz band). Since there are several comprehensive books and survey papers studying spectrum sharing between two communication systems using CR technologies, we exclude its discussion from this survey. Instead, we concentrate on the vertical coexistence of a communication system with a non-communication system in Section 7.

Given the above definitions, we show existing works in Table 1. Notice that, although there are several comprehensive surveys and books on spectrum sharing, most of them refer to CR technology, or similar terms such as dynamic spectrum access (e.g., [41,43]) and opportunistic spectrum access (e.g., [44]). In contrast, only a very limited number of works focus on general spectrum sharing methods covered in this survey. For example, several spectrum sharing methods are discussed in [29] using the coexistence of WLANs with other RF systems as examples. However, since the focus of [29] is providing background knowledge on spectrum sharing, only a few spectrum methods are discussed, such as spread spectrum techniques, directional antennas, cognitive radio, database look-up and adaptive frequency hopping. Moreover, only coexistence examples related to WLANs are discussed in [29]. Other existing surveys are dedicated to the coexistence of specific wireless networks. For example, a survey of spectrum sharing methods for Wireless Body Area Network (WBAN) is presented in [45], coexistence scenarios for 5G systems are discussed in [46], and a survey of spectrum sharing methods for the coexistence of IEEE 802.11 and IEEE 802.15.4 networks is provided in [47]. As shown in Table 1, our survey is the first comprehensive study on general spectrum sharing methods as well as their applications in various coexistence scenarios.

3. Overview of spectrum sharing methods

Due to their importance in improving spectrum efficiency, spectrum sharing methods have been widely explored in the literature. Hence, taxonomy is necessary to outline existing works and determine future research directions. In this paper, “spectrum sharing methods” denote medium access control protocols or mechanisms that an RF system uses to share the same frequency band with neighboring RF systems. In other words, coexistence methods denote specific spectrum sharing techniques, e.g., power control [48–50] and adaptive frequency hopping [51–53].

In the literature, numerous methods have been proposed to facilitate spectrum sharing among RF systems. The fundamental idea under these methods is to share spectrum opportunities in an efficient manner such that multiple RF systems coexist in the same spectrum band. In this section, we present an overview of the most widely applied techniques, ideas, and approaches to facilitate spectrum sharing. As outlined in Fig. 2, we first provide a detailed classification of the spectrum sharing methods based on whether explicit inter-network coordination is required among existing RF systems.

In coordinated methods, either global spectrum usage information is collected by the centralized entity, or local spectrum usage information is exchanged among coexisting RF systems. Given this information, spectrum sharing problems can be formulated as mathematical resource management problems, which guarantees that the resulting spectrum sharing methods are optimal with respect to certain system QoS goals (e.g., achieving maximal total throughput [54] and or minimal average delay [55]). After discussing the classification of coordinated methods, we will also discuss two common mathematical tools used in these methods: optimization theory and game theory.

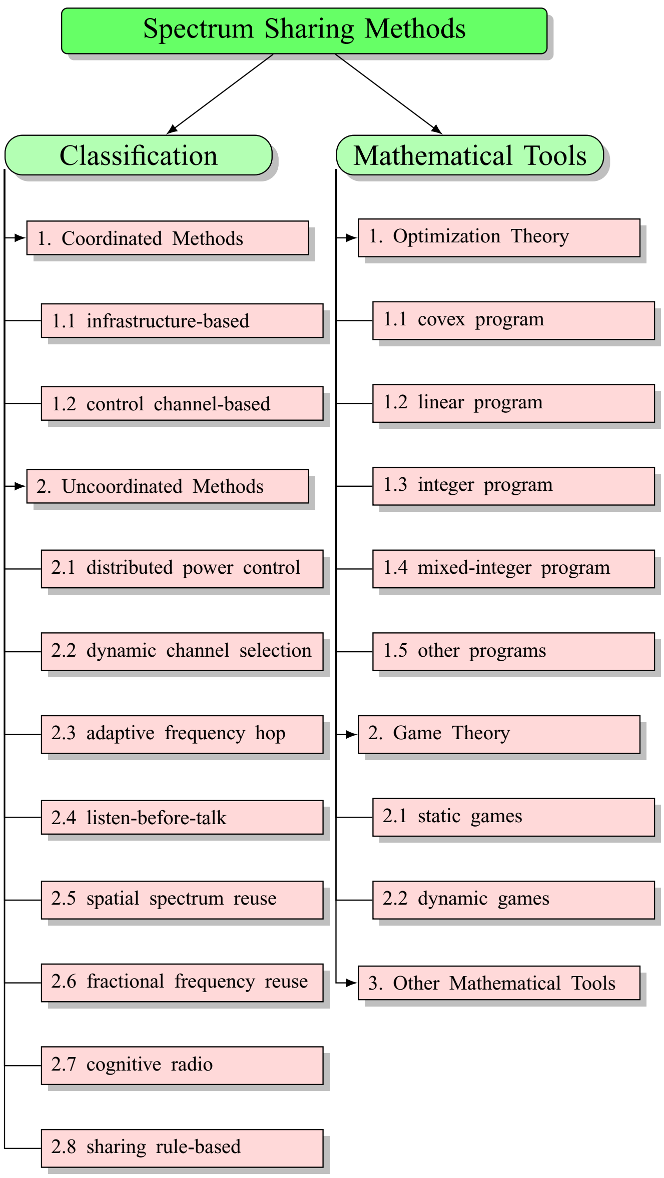

Fig. 2. Classification of spectrum sharing methods and popular mathematical tools used in the methods.

3.1. Classification of spectrum sharing methods

In the following, we discuss the classification of coordinated and uncoordinated spectrum sharing method, respectively. Coordinated methods denote those approaches that require information collection exchange or explicit coordination among coexisting RF systems to share the same frequency band. In contrast, uncoordinated methods are those approaches that require little information exchange, and coexisting RF systems adjust their own operations to coexist with neighboring RF systems. Details of the two methods are as follows.

3.1.1. Coordinated methods

Existing coordinated methods into two categories: (1) infrastructure-based method, if a centralized coordination entity is used in the method, (2) control channel-based method, if no centralized entities are used and coexisting RF systems coordinate with each other using a common control channel. Notice that infrastructure-based methods are usually implemented in a centralized scheme (e.g., IEEE 802.19.1 [56]), while control channel-based methods are usually implemented in a distributed scheme (e.g., contention-based CSMA/CA schemes used in IEEE 802.11 standard stack [57]). Hence, coordinated methods can also be classified into centralized and distributed ones. Details of the classification are as follows.

- *Infrastructure-based methods:* In infrastructure-based methods, there is usually a centralized control entity (CE) or a database responsible for the coordination of spectrum sharing among RF systems (e.g., [56,58,59]). All coexisting RF systems send their spectrum requests to the CE, and access certain frequency bands according to the decisions of the CE. The CE can separate coexisting systems in the frequency domain (FDMA), time domain (TDMA), code domain (CDMA) or space domain (through power control or using directional antennas).
  The most significant advantage of these methods is easy implementation because coexisting RF systems only need to send their spectrum requests to the control entity. Another advantage of this method is its independence of existing standards. Specifically, this method only deals with spectrum allocation among coexisting RF systems and thus does not require significant modifications to PHY/MAC techniques used by the RF systems. Moreover, since the centralized control entity allocates wireless resources to coexisting RF systems based on their requirements as well as the global coexisting environment, it can achieve efficient resource management. However, since these methods depend on expensive coordination infrastructures, they may not be feasible for many ad hoc wireless networks. Moreover, coordination overhead (i.e., all control messages) can be rather high for large coexistence systems.
- *Control channel-based methods:* In control channel-based methods, RF systems can also exchange information and coordinate with each other on a common control channel (e.g., [57,60,61]). According to these coordination methods, coexisting devices broadcast their communication parameters (e.g., device type, location, operating frequency etc.) to other devices on the control channel at the initialization of the RF system. Besides, all devices performing communication activities or requesting spectrum usage are required to broadcast busy/request tones on the control channel periodically. Multiple spectrum usage policies can be implemented such as priority-based access, micro-auction or dynamic pricing [60].
  Similar to the infrastructure-based methods, control channel-based methods can also achieve efficient resource management due to the knowledge of the global coexisting environment. Compared with infrastructure-based coordination methods, these methods are cheaper to implement because they do not require any construction of infrastructure. However, they require the existence of a common control channel, which may be impractical if no such a channel exists in the coexisting environment (e.g., no control channel is reserved in the TVWS band). Even when a common control channel is available, it can get congested easily due to large coordination overhead. For example, the control channel in the 5.9 GHz DSRC band gets congested in high vehicle density scenarios [57,62]. Furthermore, these methods usually require perfect synchronization or prior coordination among coexisting RF systems, which prove to be difficult for RF systems using significantly different PHY/MAC techniques.

3.1.2. Uncoordinated methods

Although coordinated methods are easy to implement and are supposed to achieve better coexistence performance, it may not always be feasible to have a centralized controller or a common control channel among all coexisting RF systems, or the associated overhead may be high. Instead of requiring information exchange,

Table 2
Classification of spectrum sharing methods.

Methods	Coordination	Examples	Pros	Cons
Infrastructure-based methods	Coordinated	[56,58,59]	Easy to implement, efficient resource management, few changes on existing standards	Coordination overhead, construction and maintenance of control entities
Control channel-based methods	Coordinated	[57,60,61]	Low cost, efficient resource management, distributed implementation	Coordination overhead, reservation of a common control channel, synchronization
Distributed power control	Uncoordinated	[48–50]	Simultaneous spectrum access, no synchronization requirement, coordination-free,	Spectrum sensing overhead, low efficiency due to lack of global information
Dynamic channel selection	Uncoordinated	[63–65]	Reliable protection of legacy users, local interference-free access, coordination-free	Spectrum sensing overhead, congestion on high-quality channels, power asymmetry
Adaptive frequency hopping	Uncoordinated	[51–53]	Fast discovery of free channels, flexible hopping set, protection of high-power devices	Spectrum discovery delay, unable to handle both internal and external interference
Listen-before-talk	Uncoordinated	[66,67,68]	Easy implementation, interference-free access, no synchronization, coordination-free	No fairness guarantee, low efficiency on handling inter-network coexistence
Spatial spectrum reuse	Uncoordinated	[69–71]	Simultaneous spectrum access, more practical modeling of interference	Potential hidden terminal problem, requires spatial information of coexisting devices
Fractional frequency reuse	Uncoordinated	[72–74]	Efficient inter-cell interference mitigation, coordination-free, no synchronization	Static spectrum allocation, only apply to dense homogeneous networks
Cognitive radio technology	Uncoordinated	[37,75,76]	Efficient reuse of licensed bands without affecting legacy users, coordination-free	Only apply to vertical spectrum sharing, spectrum sensing/discovery overhead
Sharing rule-based methods	Uncoordinated	[29,77,78]	Easy to implement, coordination-free, possible performance guarantees	Spectrum sensing overhead, require knowledge of neighbors before developing rules

uncoordinated methods adapt their own spectrum access strategies by observing spectrum usage of other RF systems. In the following, some uncoordinated techniques commonly used in spectrum sharing methods are presented. These methods all belong to resource allocation schemes in the aforementioned four domains: time, frequency, code, space domain, or a combination of them. As shown in Table 2, existing uncoordinated schemes can be summarized as follows.

- *Distributed power control:* Distributed Power Control (DPC) schemes allow coexisting RF systems to access the same spectrum band simultaneously such that they would not cause unacceptable interference to each other (e.g., [48–50]). DPC can be viewed as a spectrum sharing method in the space domain. DPC methods usually aim to maximize coexisting RF systems' utility subject to aggregate interference temperature limit to other heterogeneous RF systems [48], primary users of the spectrum [49], or equivalently to minimize total power consumption subject to QoS requirements of coexisting RF systems [50].
  The trade-off under these methods is that increasing an RF system's transmission power can potentially increase its utility, but all coexisting systems increasing their power simultaneously may pull down individual SINR values and violate the interference temperature limits, which degrades the utility of coexisting systems. Hence, optimal DPC schemes must be explored to facilitate the coexistence of multiple RF system. Potential tools to solve the DPC problems are non-cooperative game theory [48,49] and first-order Jacobian iterations [50]. Notice that performance of DPC solutions is usually inferior to centralized power control solutions due to lack of sufficient information exchange. However, DPC solutions are more practical especially for the coexistence of heterogeneous networks where inter-network synchronization and coordination are not supported.
- *Dynamic channel selection:* The core idea under Dynamic Channel Selection (DCS) or Dynamic Frequency Selection (DFS) methods is to enable coexisting RF systems to select the best available channel based on their local observations of spectrum usage (e.g., [63–65,79]). DCS belongs to spectrum sharing methods in the frequency domain. DFS was initially used in WLANs to protect radar operations in the 5 GHz frequency band [29], and it has been extended to resolve other spectrum sharing problems. In DFS methods, the first step is to define and measure channel quality using metrics like the level of noise power, packet error rate, and link outrage rate. Then, coexisting systems must decide the set of channels to measure due to sensing energy limits. Generally, each device can only sense a limited number of channels. Finally, each coexisting system needs to decide its channel access policy, i.e., which channels to access. As discussed in [20,79], the state of available channels can be modeled by a partially observable Markov decision process model, and there exists the so-called "exploration and exploitation" trade-off. More specifically, a device obtains an immediate reward by sensing and accessing a channel. In contrast, a device can also learn statistical information of channels states by simply sensing the channel, which helps it acquire a more future reward. Hence, the design of sensing scheduling schemes must consider the trade-off of acquiring immediate and future rewards. Moreover, reinforcement learning can also be used to choose the best channels based on past observations [79].
  One problem with DFS is that good channels can get congested easily because multiple RF systems are likely to choose the same channel simultaneously. Another problem is that high power systems can starve low power system when they access the same channel at the same time. Hence, DFS can be used jointly with power control to improve channel usage efficiency.
- *Adaptive frequency hopping:* The idea of Adaptive Frequency Hopping (AFH) is that coexisting systems change their operating channel by hopping between a pre-determined set of channels to reduce congestion on specific channels (e.g., [51,52]). Notice that AFH is a spectrum sharing method in time and frequency domains. AFH was initially used in Bluetooth, where low-power Bluetooth devices keep hopping over a subset of 79 channels to avoid interference from high-power WLAN devices [53].
  The difficulty in the design of AFH schemes is to find the efficient set of hopping channels, i.e., those with least interference from other devices. AFH has also been extended to enable the coexistence of multiple Wireless Personal Area Networks (WPANs) [52] as well as the coexistence of WPANs with other heterogeneous networks (e.g., IEEE 802.11b and Zigbee) [51]. The first step in AFH is to define and evaluate the quality of hopping sequences. Packet error rate is widely used as the channel quality metric [5,51,52]. The second step is that coexisting networks choose their hopping set in a distributed manner such that both interferences from external networks and mutual interference are minimized.

In conventional AFH methods, Bluetooth devices only need to consider interference from other heterogeneous devices, which is also called "frequency-static" interference [52]. However, due to the rapid increase of WPANs, new AFH methods have to also consider interference from coexisting WPANs (so-called "frequency-dynamic" interference [52]). In conventional AFH methods, Bluetooth devices usually avoid frequency-static interference by reducing their hopping set, which has two drawbacks. Firstly, reducing hopping set can result in overuse of remaining channels, which may violate FCC regulations [5]. Secondly, without coordination, coexisting WPANs can keep fairly similar hopping set, which increases mutual interference. Therefore, spectrum access rules are needed to enable the coexistence of a WPAN with its neighboring WPANs as well as other heterogeneous networks.

- *Listen-before-talk:* Listen-Before-Talk (LBT) is a spectrum access etiquette in which a transmitter decides whether a channel is available through a clear channel assessment check before transmitting on the channel (e.g., [66–68]). The idea under LBT is fairly simple, but its implementation and performance analysis is nontrivial. Specifically, when LBT is implemented to enable intra-network spectrum sensing, it works in the same manner as CSMA/CA for IEEE 802.11 networks. However, implementing and analyzing the performance of LBT for inter-network coexistence can be much more complicated, especially for heterogeneous networks. The reason is that these networks use different PHY and MAC techniques, and thus cannot share the same frequency band using simple CSMA/CA schemes. Instead, implementation of LBT in such cases must consider PHY/MAC features, traffic demands and interaction among the systems. To achieve fairness, a possible approach is to limit the maximum contiguous transmission time of each coexisting system such that reasonable amount of spectrum opportunities are left to other transmitters. Moreover, the choice of other LBT parameters must also be studied explicitly such as back-off time intervals, and the set of channels to listen to.
- *Spatial spectrum reuse:* In its original inception, Spatial Spectrum Reuse (SSR) allows two networks to access the same channel simultaneously on condition that they are sufficiently far from each other (e.g., [69,70]). A more efficient SSR idea is that an RF system with directional antennas can leave significant spectrum opportunities for neighboring RF systems (e.g., [71,80]). Most aforementioned spectrum sharing methods are based on "virtual interference" model, in which two devices are assumed to interfere with each other if they access the same channel at the same time. However, these models are not practical because, in reality, interference between two devices is highly dependent on their locations. In this sense, SSR methods are more practical to enable inter-network spectrum sharing.
  In an SSR method, lots of information are needed such as locations, the transmission range of coexisting devices, propagation environment etc. Lack of this information can result in hidden terminal problems [81]. Spectrum is shared in an underlying manner, meaning that transmissions from other devices are treated as noise. For the coexistence of static networks, each network determines its transmission channels and power levels subject to the interference limit to its neighboring networks. For the coexistence of mobile networks, each network can further improve spatial spectrum reuse by choosing optimal locations for its transmitting devices.
- *Fractional frequency reuse:* Fractional Frequency Reuse (FFR) is a popular technique to mitigate inter-cell interference in multi-cell OFDMA systems. It has been adopted by Mobile WiMAX and LTE standard to mitigate inter-cell interference (e.g., [72–74,82]). The main idea behind FFR is that inter-cell interference can be minimized by leveraging the significantly different inter-cell interference levels at cell-center and cell-edge users. More specifically, users close to the cell center are allowed to reuse frequency bands from neighboring sectors, whereas users close to the cell edge are assigned inter-cell exclusive frequency bands. In this way, FFR is able to achieve a better trade-off between spectral efficiency and inter-cell interference mitigation.
  FFR belongs to spectrum sharing methods in the combination of frequency and space domains. Conventional FFR methods perform a static frequency reuse policy purely based on geography information of cells, i.e., dividing users into the interior and exterior users according to their distances to the base station. Different from these methods, more and more novel FFR schemes consider a dynamic frequency reuse policy by leveraging dynamic traffic demands from different users. Although FFR was initially proposed to facilitate inter-network interference in cellular systems, it can be extended to enable the coexistence of multiple heterogeneous RF systems.
- *Cognitive radio:* Cognitive Radio (CR) allows unlicensed users to access spectrum opportunities in a band as long as they would not cause harmful interference to the licensed users of that band (e.g., [83]). The spectrum opportunities can be identified either through spectrum sensing or accessing a spectrum usage database. Some CR techniques belong to time domain spectrum sharing, where unlicensed users are allowed to access the band only when it is not being used by licensed users, i.e., overlay spectrum sharing. In contrast, other CR techniques belong to space domain spectrum sharing, where unlicensed users are allowed to use the same frequency band with licensed users without causing harmful interference to the licensed users, i.e., underlay spectrum sharing. Compared to other spectrum sharing techniques, CR technique has been extensively studied in the literature [23–25], and thus is only briefly discussed in this survey.
- *Sharing rule-based methods:* Rule-based Spectrum Sharing (RSS) [77] or so-called spectrum sharing etiquette [29] denotes distributed spectrum sharing methods in which coexisting systems access the same frequency band following certain rules. The simplest sharing etiquette includes Aloha and listen-before-talk [29]. Recall that listen-before-talk methods have been discussed above. In Aloha-based methods, a device accesses a channel with a probability and retries to access the channel if the previous transmission has collided with other transmissions. These two methods are mostly very inefficient and become more complicated when coexisting systems have different priorities of channel access. More efficient rules can be obtained by theoretically solving resource allocation problems among coexisting RF systems. The advantage of RSS is that it is easy to implement, i.e., each RF system simply follows the predetermined rules by observing local spectrum usage. Some RSS-based methods derived from solving resource allocation problems can still be associated with certain performance guarantees [77]. Although no coordination is needed when coexisting RF systems access the same spectrum band according to the rules, global information of coexisting systems is required to develop the spectrum sharing rules.

3.2. Mathematical tools used in spectrum sharing methods

Spectrum sharing problems can be formulated as global or local resource management problems in the time domain, frequency domain, code domain, space domain (deployment location or power control) or a combination of these four domains. Many mathematical tools have been applied or developed to solve these problems, among which optimization theory and game theory are the most popular ones. Hence, in this section, we discuss these two mathematical tools.

- *Optimization theory:* An optimization problem usually consists of at least one objective function and one constraint. In spectrum sharing problems, common objective functions are overall throughput, general connectivity, general link reliability, system stability, average delay, energy consumption and load balancing [29]. Constraints of the spectrum sharing problems include QoS requirements of specific networks or applications, fairness among coexisting RF systems, energy consumption limits and other physical constraints like transmission range and minimum SINR requirements. Since the formulation of optimization problems requires various information of coexisting RF systems (e.g., locations of devices, PHY/MAC parameters, traffic loads and external sources of interference etc.), they are more often used in centralized coordination methods (e.g., [39,54]).
  Optimization theory has been widely used to solve these spectrum sharing problems in the literature [15,40,84]. Optimization theory has ample branches, and the following branches are often applied in spectrum sharing problems: convex optimization [85,86], linear programing [87,88], integer programing and combinatorial optimization [89,90], mixed-integer programing [7,91]. In particular, cross-layer optimization techniques have been developed to solve resource management problems in RF systems (e.g., in [92–95]), which often consists of one or multiple aforementioned branches of optimization theory.
- *Game theory:* Game theoretical models have also been widely used to deal with spectrum sharing among RF systems (e.g., in [96–98]). A game theoretical model usually has three fundamental elements: a set of players, strategy space of each player, and payoff functions. In spectrum sharing games, each RF system acts as a player. The strategy space of a player may include the set of channels to sense or access, choice of transmission parameters (e.g., transmission power and interval), whether to cooperate with other RF systems. Many metrics can be used as payoff functions such as revenue obtained by transmitting on a certain channel, throughput, and other utility functions. In cooperative spectrum sharing games (those with information exchange among players), the objective is usually to maximize spectrum efficiency. In particular, the Nash bargaining solution is widely used in solving cooperative games, which is a unique Pareto optimal solution games modeling bargaining interactions [99]. Dynamic games are usually used to study the long-term interaction of coexisting RF systems [100].
  One prominent advantage of game theoretical methods is that they are able to model behaviors of coexisting RF systems in a practical and reasonable manner by explicitly exploring strategy spaces and utilities of all game participants. On the other hand, one problem with these methods is that they require extensive information exchange among coexisting systems. Moreover, although Nash Equilibria can be obtained, they may not necessarily be Pareto optimal.

Note that since our paper is focused on the underlying PHY/MAC techniques used in these methods instead of the specific mathematical tools used to solve the formulated coexistence problems, the main text follows the classification of coexistence methods based on the underlying PHY/MAC techniques. However, since some mathematical tools like game theory can also provide insights on the methods, we also highlight these tools in our discussion of these methods.

4. Coexistence of homogeneous networks

As outlined in Table 3, in this section, we consider some specific examples of coexistence of homogeneous networks as well as practical spectrum sharing methods used to facilitate the coexistence.

Table 3
Examples of coexistence of homogeneous networks.

Coexistence scenarios	Coordinated methods	Uncoordinated methods
WLAN & WLAN	[101–103]	[104,105]
WRAN & WRAN	[106–110]	[111]
WPAN & WPAN	[112–114]	[52,115,116]
Cellular & Celluar	[117–119]	[120–122]
Femtocell & Femtocell	[123–125]	[126–128]

4.1. Coordinated methods for homogeneous networks

Compared with other coexistence scenarios, coordination among homogeneous networks is easier because all coexisting networks use the same PHY/MAC techniques. Some standards like IEEE 802.22 and LTE even include coordinated inter-network interference mitigation schemes. In the following paragraphs, we discuss spectrum sharing methods in the coexistence of homogeneous Wireless Local Area Network (WLAN), Wireless Regional Area Network (WRAN), Wireless Personal Area Network (WPAN), cellular and femtocell networks.

(a) WLAN & WLAN. WLANs are almost the most popular wireless networks due to explosive growth of portable devices. Hence, it is quite meaningful to design efficient spectrum sharing schemes between neighboring WLANs. A centralized frequency assignment mechanism is proposed in [101] to enable the coexistence of multiple WLANs. In this mechanism, both co-channel and adjacent channel interference relationship of coexisting WLANs is modeled by a graph where vertices represent access points (APs) of the WLANs. Then, a frequency assignment algorithm is developed based on graph coloring theory, which maximizes total throughput of the coexisting WLANs. The algorithm can be implemented in both centralized (infrastructure-based) and distributed (control channel-based) ways. In the centralized scheme, a central entity collects information of the WLANs, implements the frequency assignment algorithm, and sends frequency assignment decisions to the WLANs. In the distributed scheme, coexisting networks exchange the frequency assignment information on a control channel.

In [103], a distributed spectrum sharing method is proposed with both channel allocation and load balancing through cell breathing. In particular, the new communication overhead incurred by the spectrum sharing method is analyzed. More specifically, the authors assume that each AP has two interfaces: one for normal AP operations, and the other for inter-network communication. Neighboring APs keep exchanging their transmission information, based on which a channel allocation algorithm and a load-balancing algorithm are performed to maximize spectrum usage among the neighboring WLANs. We can see that this method belongs to the control channel-based methods.

(b) WRAN & WRAN. As the first standard on cognitive radios, the IEEE 802.22 standard is becoming more popular in both the academy and industry [106,129], especially after the formal release of the TVWS band for cognitive access [130]. Since the radius of an IEEE 802.22 network can be as large as 100 km, it is also termed Wireless Regional Area Network (WRAN) [106]. In this standard, the coexistence of multiple 802.22 networks is also termed “self-coexistence” [106]. A Coexistent Beacon Protocol (CBP) is included in the standard to support self-coexistence. In this protocol, each 802.22 frame includes a self-coexistence window during which coexistence beaconing packets are exchanged over-the-air (corresponds to “Infrastructure-based Coordination” in Section 3) or through the backhaul (corresponds to “Common Channel-based

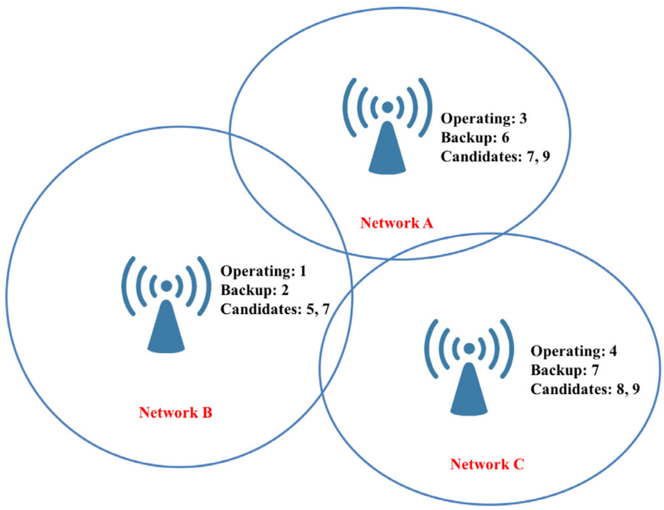

Fig. 3. IEEE 802.22 self-coexistence example.

Coordination" in Section 3). The beaconing packets are utilized to find neighboring 802.22 networks.

CBP includes two spectrum sharing policies: spectrum etiquette and on-demand spectrum contention. In the spectrum etiquette protocol, all neighboring networks will change their channel setting accordingly after one network changes its channel setting. An example is illustrated in Fig. 3. Assume that two primary users appear in Network *A* occupying channel 3 and 6, respectively. Then, Network *A* has to promote channel 7 and 9 as its operating and backup channel, respectively. Both Networks *B* and *C* then perform spectrum etiquette after receiving the channel set update information from Network *A*. Specifically, Network *B* removes channel 7 from its candidate channel list. Network *C* not only removes channel 7 and 9 from its backup and candidate channel lists, but also promotes channel 8 to be its backup channel. In this way, the three networks can decrease the possibility of potential channel conflicts. Note that the standard also applies to the cases where more than two networks overlap, which is not discussed in this paper.

The on-demand spectrum contention protocol is similar to the CSMA/CA protocol used for MAC in 802.11 networks, in which coexisting nodes contend for the same channel through the random back-off mechanism. After the publication of the 802.22 standard in 2011, many other coordinated self-coexistence schemes have been proposed, such as two channel assignment schemes for cooperative and non-cooperative 802.22 devices [131], traffic-aware self-coexistence management [132], fuzzy logic control-based inter-network coexistence protocol [108], and self-coexistence among interference-aware IEEE 802.22 networks with enhanced air-interface [133].

In particular, a cooperative real-time spectrum sharing protocol is developed in [101]. The proposed On-Demand Spectrum Contention (ODSC) protocol employs interactive MAC layer messaging on an inter-network communication channel to provide efficient, scalable, and fair spectrum sharing among WRANs. Therefore, it belongs to the control channel-based coordinated methods. The protocol works as follows. Before initiating MAC layer messaging process, a WRAN demanding additional spectrum resources first selects a channel on which no incumbents are detected. Then, it verifies whether the selected channel can be shared by employing transmit power control technique. If it is feasible, the WRAN schedules its data transmissions on the selected channel with appropriate power control settings. Otherwise, ODSC messaging takes place allowing cooperative spectrum contention among WRANs to share the target channel in a time-sharing manner.

In addition, auction theory is used to facilitate dynamic spectrum sharing among multiple WRANs in [109]. Specifically, a credit token-based auction mechanism is devised for coexisting WRANs to either offer or rent their spectrum resources. To start an auction, either a renter WRAN initiates broadcasting of spectrum resource requests, or an offeror WRAN indicates the intent to share its resources by broadcasting resource advertisement messages. One common drawback of many ascending bid auction mechanisms is renters must keep bidding up prices to the offeror, and receive the results of bidding repeatedly, which incurs a significant amount of signaling overhead. We can see that similar methods using gaming models relay on a control channel to exchange price information, and thus the signaling overhead is an important issue. To reduce signaling overhead, the authors develop a Vickrey-based auction mechanism, which requires renters to bid and receive the bidding results only once. Therefore, the signaling overhead of the new bidding scheme is much lower. A similar game model is also proposed in [110], which consists of a spectrum offering-renting mechanism as well as a spectrum contention mechanism.

Another cooperative spectrum sharing method is proposed in [134] to improve spectrum usage efficiency through the information exchange among neighboring SUs in the TVWS band. Instead of adopting a contention spectrum access mechanisms as used in IEEE 802.22, the authors develop a reinforcement learning scheme to merge and leverage the spectrum usage information of neighboring SUs. Although this scheme is developed for individual SUs, it can also apply to the coexistence of multiple WRANs, where base stations of the WRANs perform the reinforcement learning scheme to coexist with each other.

(c) WPAN & WPAN. Different from the IEEE 802.22 standard, some standards may not include self-coexistence mechanisms, e.g., IEEE 802.15.4-based Wireless Person Area Networks (WPANs). In this case, new spectrum sharing methods are needed to enable coexistence of multiple such networks. As an example, a simulation study is conducted in [113] to evaluate the interaction between two coexisting WPANs using both contention-based CSMA schemes or contention-free slot allocation schemes. The simulation results demonstrate that the inter-network interference can significantly degrade the performance of the two WPANs without efficient spectrum sharing mechanisms.

The coexistence problem is also studied in [112], in which the proposed method maximizes both spatial and time domain frequency utilization under channel gain uncertainties, in order to minimize the number of frequency channels required to accommodate a certain number of coexisting IEEE 802.15.4 networks. In this method, each WPAN has a control node (CN) who coordinates with the CNs of neighboring WPANs. Specifically, the coexistence problem is first formulated as an optimization problem with the objective of maximizing intensity of simultaneously active CNs on one channel, subject to the limit on outage probabilities in neighboring WPANs. The only decision variable is a carrier-sensing threshold, and the trade-off of determining the threshold is as follows. Increasing the carrier sensing threshold decreases the contention domain of each CN, and thus increases the number of CNs that can use the same logical channel. However, it increases the interference level and the outage probability. A stochastic geometry approach is developed to solve the optimization problem, and a superframe structure for the coexisting IEEE 802.15.4 networks is designed.

Another cooperative spectrum sharing scheme is proposed in [114] to eliminate mutual interference among neighboring 802.15.4 networks. The scheme consists of two phases: coexistence detection and coexistence mitigation. In the first phase, CN of each 802.15.4 network keeps sensing its operating channel to detect "harmful" interference from neighboring 802.15.4 networks. Here, "harmful" is characterized by the criterion that current throughput of the 802.15.4 network is less than a threshold. If harmful interference is detected by some CNs, the coexistence mitigation phase will be activated. In this phase, a coexistence manager (CM) collects transmission information from CNs of coexisting networks and rearranges MAC super-frames for the CNs such that colliding CNs have non-overlapping super-frames. Due to the use of CMs, this method belongs to the infrastructure-based methods.

(d) Cellular & Cellular. The Cooperative Multi-Point (CoMP) scheme has been proposed to improve cell edge user data rate and spectral efficiency in LTE and LTE-Advanced [117–119,135]. The fundamental idea of CoMP is very similar to Multiple Input Multiple Output (MIMO) technology, i.e., to utilize multiple transmitting and receiving antennas at multiple locations (that may or may not belong to the same physical cell) to enhance the received signal quality at receivers. In CoMP techniques, a new terminology "Transmit Point" (TP) is defined as a set of collocated antennas and a cell can correspond to one or more TPs.

Essentially, CoMP can be defined as techniques dealing with coordination of TPs. CoMP techniques consist of three components: coordinated scheduling and coordinated beamforming (CS/CB), joint transmission (JT), and TP selection (TPS). Specifically, CS/CB regulate how coordinated TPs share channel state information (CSI) of multiple User Equipment (UE) on a control channel and cooperate to mitigate mutual interference. The rationale of CS/CB is that coexisting TPs coordinate to select transmit precoders in each TP, such that inter-TP interference is minimized. JT denotes the simultaneous transmission of data packets from multiple TPs to a single UE with appropriate beamforming weights. This way, cell-edge terminals can achieve higher performance by converting interference signals to desired signals. Finally, TPS works by allowing a UE to report the ID of its preferred TP (e.g., the TP with the highest received SINR), and the selected TP is then scheduled to serve the UE. CoMP is a high-complexity joint PHY/MAC inter-cell spectrum sharing solution, which belongs to the "Infrastructure-based Coordination" method outlined in Section 3 due to the usage of backhauls to inter-connect BSs.

(e) Femtocell & Femtocell. Due to the small coverage of a femtocell, it is common that a lot of femtocells are deployed in an indoor environment, which makes the inter-cell interference problem challenging [123]. A centralized spectrum sharing algorithm is proposed in [123] based on joint sub-channel allocation and power control. Specifically, the coexistence problem is first formulated as an optimization problem with the objective of maximizing total expected capacity of all coexisting femtocells, in which the weight of a femtocell is proportional to its traffic load. Due to NP-hardness of the problem, the authors develop an enhanced modified iterative water-filling algorithm to achieve a sub-optimal solution. An important feature of the algorithm is that each cell performs power allocation to minimize the interference that it causes to a heavy-traffic cell to ensure the inter-cell fairness. Since the traffic load information must be shared among coexisting networks, this method is a control channel-based method.

Another cooperative spectrum sharing scheme is proposed in [124] to overcome inter-femtocell interference. The scheme is a cross-layer scheme with joint cooperative MAC layer user scheduling and PHY layer beamforming techniques. Firstly, femtocell base stations collaboratively schedule users to minimize the average interference on spatially correlated channels. Then, either coherent beamforming or statistical eigen beamforming is selected according to the operation condition to maximize the network spectral efficiency. Since only spatial correlation coefficient is shared among the base stations, the proposed spectrum sharing scheme is a control channel-based method with low coordination overhead.

In [125], the authors propose another cross-layer spectrum sharing method based on adaptive fractional frequency reuse. In this method, a centralized femtocell gateway analyzes the impact of mutual interference among coexisting femtocells based on location information femtocells. Then, it classifies femtocells into a number of groups according to the amount of interference they generate to others. Thereafter, it calculates the minimum number of orthogonal subchannels for each group to guarantee required QoS performance near the cell boundary. Finally, the transmit power of each femtocell is adjusted based on the received signal strength in a distributed manner. It is shown that the proposed scheme can provide reasonably high ergodic system spectral efficiency while assuring the required QoS performance near the cell boundary.

4.2. Uncoordinated methods for homogeneous networks

In the following paragraphs, we discuss uncoordinated spectrum sharing methods in the coexistence of homogeneous WLANs, WRANs, WPANs, cellular and femtocell networks.

(a) WLAN & WLAN. A Regular Channel Access (RCA) method is proposed in [104] to improve the coexistence between neighboring 802.11 networks. The proposed method is an extension to the HCCA channel access method defined in IEEE 802.11e. Specifically, coexisting 802.11 networks contend to access the same channel through the CSMA/CA scheme. Moreover, similar to IEEE 802.11e, coexisting networks can have different priorities such that QoS can be supported. However, the method requires significant changes to existing IEEE 802.11 standards, and thus may be impractical to implement. We can see that this method is based on the listen-before-talk principle, and a similar method is also proposed in [102].

Coexistence of different Wi-Fi networks is studied in [105]. In this work, the authors consider the problem of channel conflicts among Access Points (APs) from different service providers. The problem is formulated as a game where service providers are players, and the action that each player can take is the assignment of a set of channels to its APs. The authors consider the price of anarchy, which is defined as the ratio between the total coverage of the APs in the worst Nash equilibrium of the game and what the total coverage of the APs would be if the channel assignment were done by a centralized controller. They provide theoretical bounds on the price of anarchy based on assumptions on the underlying network, as well as the type of bargaining allowed between service providers. The fundamental tool in the analysis is to find Nash Equilibrium of the game by solving a maximal coloring problem in an appropriate graph. In this work, the authors show that price of anarchy of these games is related to the approximation factor of local optimization algorithms for the maximum k-colorable subgraph problem.

(b) WRAN & WRAN. An inter-BS Coexistence-aware Spectrum Sharing (CASS) protocol is proposed in [111] to support horizontal coexistence of WRAN. The protocol is based on the dynamic channel selection technique discussed in Table 2. CASS has the following noteworthy properties: (1) it supports both non-exclusive and exclusive spectrum sharing, and can dynamically switch between the two to minimize self-interference, while keeping control overhead (induced by channel contentions) under control. (2) It uses a novel channel selection algorithm that utilizes spectrum sensing results to minimize potential interference to incumbent users. (3) It utilizes an inter-BS channel contention procedure that enables a BS in need of more spectrum resources to borrow channels from its neighboring cells.

(c) WPAN & WPAN. In [52], several dynamic AFH-based methods are proposed for the coexistence of multiple collocated Wireless Personal Area Networks (WPANs). In these methods, each WPAN dynamically selects a subset of frequency channels for hopping such that mutual interference is minimized. Packet error rate is measured and used as an input to the proposed methods, which enables the dynamic AFH to avoid interference from frequency-static interference sources (e.g., Wi-Fi devices). Since WPAN devices could cause harmful interference to low-power non-WPAN devices, an etiquette rule is also proposed to characterize the behavior of the collocated WPANs with dynamic AFH as a single collective entity that produces interference. The operation of dynamic AFH is robust and adaptive to the dynamic changes in the environment and to the noise levels on the channel.

Another simple distributed spectrum sharing method is proposed in [115] to enable coexistence of multiple WPANs on the same channel. The spectrum sharing is realized through a "co-existence test". Specifically, the control node of a new WPAN with transmission demands must learn neighboring environment via spectrum sensing before it assigns frames to its client nodes. Based on the strength of received signals from neighboring WPANs, the control node classifies them into two categories: interfering and non-interfering WPANs. Then, the control node tries to find non-overlapping time slots with the interfering WPANs. If some slots are found, it assigns them to its client nodes. Otherwise, it switches to another channel. Although this scheme can ensure elimination of inter-network interference, its sensing overhead can be high because the control node must discover not only interfering WPANs, but also their inactive periods. We can see that the fundamental idea of this method is similar to listen-before-talk.

IEEE 802.15.4 uses a contention-free guaranteed time slot (GTS) mechanism to eliminate internal contention within a network. However, this mechanism cannot ensure successful transmissions with neighboring active 802.15.4 networks due to lack of inter-network coordination. Given this observation, the authors in [116] propose a clear channel assessment (CCA) scheme to eliminate inter-network transmission collisions, which is similar to listen-before-talk. According to this scheme, instead of transmitting immediately at its allocated GTS, an 802.15.4 device must sense the channel at the beginning of its GTS. If no other transmissions from neighboring WPANs are detected, the device can continue to transmit. Otherwise, it has to wait until the detected transmission is finished. A problem with this uncoordinated scheme is that it requires changes to the existing IEEE 802.15.4 standard in MAC layer.

(d) Femtocell & Femtocell. A fully distributed method is proposed in [126] for dynamic spectrum sharing between femtocells. First, the available frequency band is divided into a number of channels with the same bandwidth. Then, the spectrum sharing problem is converted to a distributed dynamic channel selection problem, where each femtocell selects a subset of available channels by considering both spectrum usage efficiency and mutual interference. More specifically, assuming a symmetric interference relationship, coexisting femtocells can be represented by vertices in a graph, and edges between vertices denote the interference relationships. Given such a graph, a clique is defined as a subgraph where every pair of vertices in this subgraph share an edge. Hence, the maximal clique denotes the densest spectrum reuse that can be achieved in a particular area while keeping an orthogonal channel allocation in femtocells.

The goal of the proposed distributed method is to find the maximal clique. The proposed method consists of two iterative loops: the outer loop determines a feasible frequency reuse, and the inner loop allocates channels to each femtocell such that mutual interference is minimized. Starting from a random frequency reuse, each femtocell makes several attempts to eliminate mutual interference. The number of attempts is controlled by a timer, and a new sparser frequency reuse attempt is started after the timer expires. Hence, this method is named a timeout-based reuse selection approach.

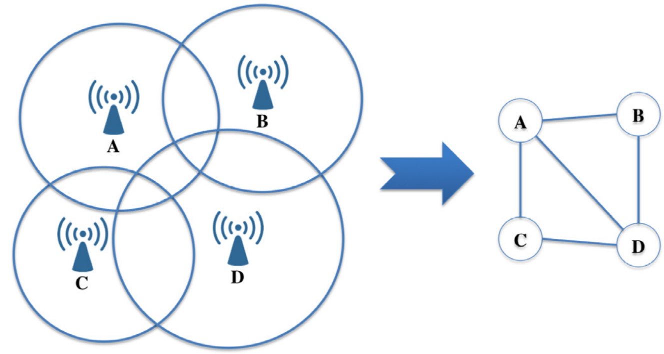

Fig. 4. Example of general ICI links.

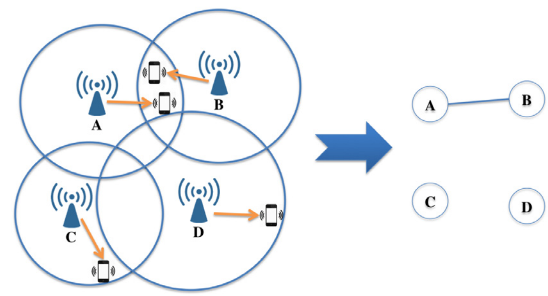

Fig. 5. Example of actual ICI links.

Another distributed spectrum sharing method named "soft frequency reuse" (SFR) is proposed in [127] to enable the coexistence of densely deployed LTE-based femtocells. SFR is a variation of the traditional "fractional frequency reuse" (FFR) method for LTE as discussed in Section 3. A remarkable difference between SRF and FFR is that SFR dynamically divides the bandwidth in each cell based on the number of interfering femtocells. More specifically, a femtocell BS mitigates its interference with neighboring femtocells through adjusting its transmission power for downlink transmissions and assigning different channels to cell-center and cell-edge users based on the number interfering femtocells for uplink transmissions.

A contention-based spectrum sharing method is proposed in [128] to facilitate the coexistence of densely deployed self-organizing femtocell networks. Different from traditional CSMA-like schemes, the authors employ a two-tier contention scheme consisting of two phases: contention-scheduling and resource assignment. In the contention-scheduling phase, each femtocell BS selects a user that contends with users selected by neighbor BSs for the next allocation interval. In the resource assignment phase, the user who wins the contention transmits packets in the next allocation interval. The pro of this method is that the contention is based on actual inter-cell interference (ICI) links instead of general co-located "interfering cells", which improves spectrum usage efficiency through allowing multiple transmission links on the same channel. A specific example is presented below.

As shown in Fig. 4, two cells are mutually interfering if they have overlapping areas, and the interference relationship can be represented by a so-called "general ICI link" in an interference graph. In contrast, as shown in Fig. 5, two cells are mutually interfering if the actual transmission in these cells interfere with each other, and the interference relationship can be represented by a so-called "actual ICI link" in an interference graph. For example,

Table 4
Examples of the coexistence of heterogeneous networks.

Coexistence scenarios	Coordinated methods	Uncoordinated methods
Cellular & Ad Hoc	[136]	[137–139]
WLAN & WPAN	[140–142]	[42]
WLAN & Bluetooth	[143]	[144–148]
WRAN & 802.11af	[149–151]	[152–154]

since the actual transmissions in Cell *C* and *D* do not interference with each other, there is no actual ICI link between these two cells. Hence, a single channel can be used by only one cell in Fig. 4 at any time, while the channel can be used by cell *C*, *D*, and one of *A* and *B* simultaneously. Therefore, the spectrum usage efficiency in Fig. 5 is two times higher than that in Fig. 4.

4.3. Comparison between coordinated and uncoordinated methods

In the previous two parts, we have discussed specific coordinated and uncoordinated methods for the coexistence of homogeneous networks, respectively. In addition to the pros and cons summarized in Table 2, we discuss the differences between these methods in terms of enabling coexistence of homogeneous networks

From the above analysis, we can conclude that coordinated methods like the self-coexistence protocol in IEEE 802.22 are more appropriate for the coexistence of homogeneous networks. The first reason is that coordinated method can usually achieve higher spectral efficiency due to possible optimization of spectrum usage. The second reason is that the cost of including new self-coexistence functionality in existing wireless standards (e.g., Wi-Fi and ZigBee networks) can be negligible. Specifically, to add the self-coexistence functionality to new devices, the standard groups only need to provide corresponding amendments to the standards without affecting old devices. For example, if two new devices have the self-coexistence functionality, both of them can operate in a spectrum sharing mode such that they can share the same frequency band. If a new device coexists with an old device, since the old device does not have the self-coexistence functionality, the new device also operates in a non-spectrum sharing mode, which would not affect the old device.

Lastly, the signaling overhead in the coordinated methods can be largely reduced through judiciously designed spectrum sharing algorithms or protocols. Specifically, since synchronization among homogeneous networks can be easy to achieve, broadcasting can be used to reduce signaling overhead. More importantly, many spectrum sharing algorithms can be optimized such that only a little amount of information needs to be shared among coexisting networks (e.g., the aforementioned [103,109,124]). Therefore, coordinated methods with low signaling overhead have greater potential to facilitate the coexistence of multiple homogeneous networks.

5. Coexistence of two heterogeneous networks

In this section, we consider the coexistence of two heterogeneous networks. Compared with the coexistence of homogeneous networks, the coexistence of heterogeneous networks is much more challenging, since coexisting networks can use significantly different PHY/MAC protocol and resource allocation techniques. Some coexistence examples and their corresponding spectrum sharing methods are listed in Table 4. Next, we discuss these coordinated and uncoordinated methods in Sections 5.1 and 5.2, respectively.

5.1. Coordinated methods for heterogeneous networks

Although almost no wireless standards include spectrum sharing schemes with other wireless standards, it is rewarding to modify these standards to improve their spectrum usage efficiency. In this part, we discuss some coordinated spectrum sharing methods facilitating the coexistence of two heterogeneous networks.

(a) Cellular & Ad Hoc. A cooperative spectrum sharing method is proposed in [136] for the coexistence of a cellular network and an ad hoc network. The motivation for the cooperation is that the cellular network can improve the throughput of its cell-edge users with the help of the ad hoc network while the ad hoc network can obtain extra spectrum resources from the cellular network. More specifically, the coexistence problem is formulated as an optimization problem with the objective of maximizing the ad-hoc transmission capacity, subject to the constraints on the outage probability of the ad-hoc network and on the throughput improvement ratio of the cellular network. Decision variables of the optimization problem are deployment density of the ad hoc network and time ratio allocated to ad hoc network. Both the capacity of the ad-hoc network and the average throughput of the cellular network are characterized using stochastic geometry theory, and a heuristic algorithm is devised to solve the problem.

(b) WLAN & WPAN. The IEEE 802.15.4 Wireless Sensor Networks (WSNs) and WPANs with low power consumption and low cost are widely adopted in low data rate industrial and consumer applications. The relatively high power IEEE 802.11b/g WLANs offer high data rate and larger range. Both these technologies coexist in the ISM band, which creates a challenging coexistence environment for WPANs due to the power asymmetry. To address the coexistence problem, a Frame Converter (FC) system is developed in [140] to establish cooperative coexistence between a WLAN and a WPAN. More specifically, the FC has both the IEEE 802.15.4 and Wi-Fi radio interfaces. It converts the IEEE 802.15.4 frame into Wi-Fi frame at one interface and converts back into IEEE 802.15.4 frame at the other interface. This conversion allows the IEEE 802.15.4 network to use the infrastructure of the WLAN. Hence, the radio range of the IEEE 802.15.4 network is extended to that of Wi-Fi. It enables cooperative coexistence between the IEEE 802.15.4 WPANs and WLANs.

A centralized spectrum sharing method is proposed in [141], in which an Interference Mediator (IM) is used to eliminate mutual interference between a WLAN and a ZigBee WPAN. More specifically, the IM first detects mutual interference by periodically gathering frame error rate values from ZigBee nodes. If severe interference is detected, the IM proceeds to eliminate the interference by allocating spectrum resources to the WLAN and WPAN in a TDMA manner.

A cooperative carrier signaling (CCS) scheme is proposed in [142] to harmonize coexisting WPAN and WLAN devices. The cooperative signaling scheme is triggered on a control channel when WLAN interference is present and causes severe collisions in the WPAN. The CCS scheme employs a separate WPAN node to emit a carrier signal (busy tone) concurrently with the desired WPAN nodes' data transmission, thus enhancing the WPAN nodes' visibility to WLAN nodes. Since the busy tone has a transmit power comparable with that of WLAN nodes, the CSMA scheme used by Wi-Fi nodes guarantees fairer spectrum usage between WPAN and WLAN nodes. Extensive experiments conducted by the authors show that CCS scheme reduces collision between WPAN and WLAN by 50 percent for most cases, and by up to 90 percent in the presence of a high-level interference, all at negligible WLAN performance loss. This spectrum sharing scheme is essentially coordinated in the sense that the selected WPAN node contends with WLAN nodes using CSMA/CA on the same channel.

(c) WLAN & Bluetooth. Two overlapping avoidance mechanisms are proposed in [143] to mitigate interference between a WLAN and a Bluetooth network. Both of the mechanisms are MAC layer traffic scheduling techniques. More specifically, the first mechanism avoids overlapping operation time between the Bluetooth voice traffic and the 802.11 data packets by performing a scheduling of the traffic transmissions at the WLAN stations. In contrast, the second mechanism utilizes the variety of Bluetooth packet lengths to avoid channel usage overlapping between 802.11 and Bluetooth transmissions. These two mechanisms can be implemented in either collaborative or non-collaborative way depending on how one system acquires spectrum usage pattern of the other system.

(d) WRAN & 802.11af. The IEEE 802.22 and IEEE 802.11af are the first two standards dedicated to the TVWS band and are expected to be widely adopted in the future [149]. Hence, the coexistence between these two networks is very important to the future spectral efficiency of the TVWS band. This coexistence scenario is similar to the coexistence of a WLAN and a WPAN in the sense that one system uses significantly higher transmit power level than the other system. The difference, however, is that WRANs and IEEE 802.11af networks operate in the licensed TVWS band while WLANs and WPANs operate in the license-exempt ISM band.

A busy-tone scheme is proposed in [149] to enable co-channel coexistence of a WRAN and an IEEE 802.11af network, which is implemented at the WRAN customer-premises equipment (CPE). More specifically, 802.22 CPEs send out busy tone signals with known pattern with 100 mW power that is the transmit power used by 802.11af devices. After detecting the busy tone signals, the 802.11af devices must postpone their transmission to avoid interference. In this way, WRAN receivers can be protected from hidden 802.11af terminals. Moreover, 802.11af devices can avoid interference from WRAN devices by identifying detected CPEs and learning their transmission patterns. Another similar busy-tone scheme can be found in [150]. To ensure fair spectrum sharing between the two networks, a centralized selfishness-aware scheme is proposed in [151]. In this scheme, a spectrum coordinator allocates spectrum resources to the two networks. The spectrum sharing problem is formulated as a 0–1 multiple knapsack problem with the objective of maximizing overall spectral efficiency via joint bandwidth and channel allocation. Due to NP-hardness of the problem, a polynomial-time approximation algorithm is proposed to solve it.

5.2. Uncoordinated methods for heterogeneous networks

In this part, we discuss the uncoordinated spectrum sharing methods used in the coexistence scenarios in Table 4.

(a) Cellular & Ad Hoc. A spectrum sharing method based on distributed power control is proposed in [137] to improve spectrum efficiency in cellular networks. The fundamental idea in this book is that a Device-to-Device (D2D) communication mode can outperform the Device-to-Base Station (D2B) mode. More specifically, the authors first show that, even in a spectral efficient network, cellular users can exploit the network topology to achieve better communication performance. Then, they propose a D2D communication mode where cellular users can communicate directly with each other rather than using the base station. Hence, the coexistence scenario can be viewed as the coexistence between a low-power ad-hoc network (D2D) and a high power cellular network (D2B). To coexist with the cellular networks, D2D users control their power such that they would not cause unacceptable interference to uplink transmissions. Finally, both analytical and simulation results are provided to show that the D2D scheme is a feasible option for next generation cellular networks. However, power control may not be sufficient to protect uplink transmissions since D2B users can be very close to D2D users. Moreover, interference from high power downlink transmissions should also be considered such that D2D transmissions will not fail due to interference from the downlink transmissions.

Another distributed power control algorithm is proposed in [138] to facilitate the coexistence of a D2D ad hoc network and a cellular network. The proposed coexistence system is very similar to the spectrum sharing between a primary system and a secondary system in CR technology. More specifically, the ad hoc network is allowed to use cellular channels on condition that it would not cause harmful interference to cellular transmissions. In the proposed spectrum sharing method, the authors first derive the interference from D2D link to cellular link as a function of the ratio of the distance between the base station and D2D transmitter and the distance between the D2D transmitter and D2D receiver. Finally, the maximum transmission range of the D2D link is calculated in the sense that the interference to cellular links is less than a threshold. Another similar CR-like spectrum sharing mechanism between a cellular network and an ad hoc network is proposed in [139].

(b) WLAN & WPAN. Coexistence between an 802.11g WLAN and an 802.15.4 sensor network is studied in [42]. Three significant differences between the two standards result in the asymmetry of the coexistence problem. First, the transmit power of 802.11g devices (above 15 dBm) are much higher than that of 802.15.4 devices (as low as 0 dBm). Second, 802.15.4 networks are usually large environment monitoring networks, while 802.11g networks are mostly local small hotspots around Access Points (APs). Finally, in terms of objectives, 802.11g networks require high-throughput MAC protocols, while 802.15.4 networks prefer low-delay MAC protocols.

Given these differences, a dynamic channel selection method is proposed to improve the performance of the 802.15.4 network under varying interference levels from the 802.11 network, which is another "Dynamic Channel Selection" method as discussed in Section 3. Furthermore, three channel selection algorithms are proposed and compared: random frequency selection, simulated annealing, and learning-based distributed approaches. In particular, the learning algorithm selects a channel for the next period that is expected to have the best channel quality. Simulation results show that the simulated annealing and learning-based channel selection algorithms significantly outperform the random frequency selection in terms of average packet delay in the 802.15.4 network.

(c) WLAN & Bluetooth. An "Adaptive Frequency Hopping" (AFH) method is proposed in [144] for the coexistence of Bluetooth and IEEE 802.11b systems. The authors propose a novel approach called interference source oriented adaptive frequency hopping-based on a memory and power efficient channel classification procedure. It is shown that the approach is able to reduce time and space complexity of the coexistence mechanism. A similar approach has been adopted in [145] to deal with the coexistence of 802.15.4 with 802.11 networks using an adaptive frequency selection scheme.

A role-switching mechanism is proposed in [146] to optimize the coexistence of WLANs and Bluetooth networks. Instead of individual Bluetooth devices, the authors consider centralized Bluetooth networks (or piconets), in which a master Bluetooth node manages both downlink and uplink transmissions in its piconet. The master node can be selected dynamically. In this case, the authors study the coexistence of WLANs with multiple piconets. The coexistence problem is formulated as an integer linear programing

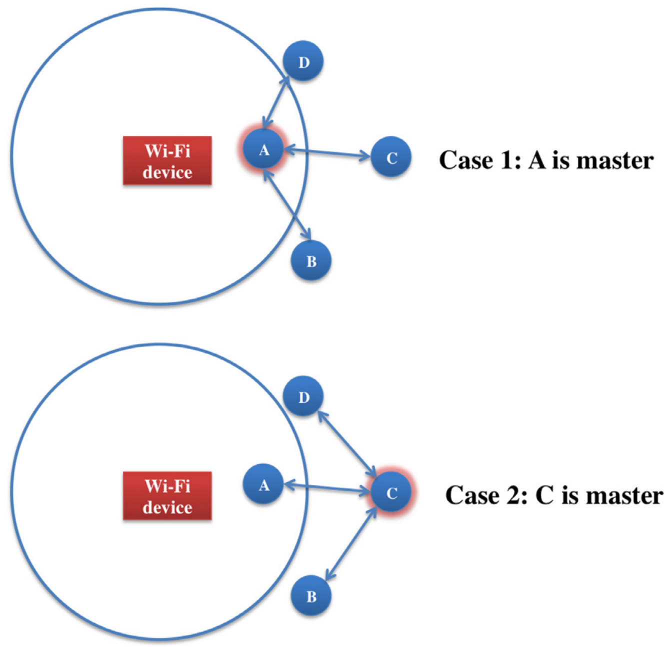

Fig. 6. Two examples of Bluetooth master node choice.

problem with the objective of minimizing total mutual interference via smart selection of master nodes in piconets.

The motivation of the master node selection is illustrated in Fig. 6 where there are two selection cases. In the first case, node *A* is selected as the master node, and we can see that the Wi-Fi device interferes with all the three Bluetooth links, i.e., $A-B$, $A-C$ and $A-D$. In contrast, in the second case, node *C* is selected as the master node, and only link $A-C$ is affected by the Wi-Fi device. The master node selection problem becomes more complicated when there are multiple Wi-Fi devices as well as multiple piconets, in which both the interference between Wi-Fi devices and piconets and the mutual interference between neighboring piconets must be considered. One flaw of this work is that the authors do not develop specific master selection algorithms with certain performance guarantees. Instead, only numerical results are provided.

A channel clustering scheme and a probabilistic channel visiting scheme are proposed in [147] to mitigate mutual interference between multiple WLANs and multiple piconets. Most existing uncoordinated methods use packet error rate (PER) or received signal strength indication (RSSI) to evaluate the quality of a WLAN channel. However, these methods fail to consider mutual interference among piconets. To address this problem, the authors in [147] propose a channel clustering scheme that can accurately find low-quality WLAN channels using statistical pattern recognition techniques. Moreover, considering dynamics of WLAN channels, the authors develop a simple probabilistic channel-visiting scheme, which allows piconets to access low-quality WLAN channels with certain probabilities with the motivation that the channel quality can change over time. However, explicit analysis of the impact that the proposed schemes can have on system performance is not provided in this work.

Instead of considering potential interference that high-power Wi-Fi devices can cause to low-power Bluetooth devices, the opposite problem is studied in [148]. Specifically, the authors devise an MAC layer packet length optimization scheme for Wi-Fi devices to avoid interference from Bluetooth devices. Based on the current packet error rate, the Wi-Fi devices dynamically adjust their packet fragmentation to avoid the interference from Bluetooth devices. One problem with this scheme is that the MAC layer packet error rate may not necessarily result from Bluetooth interference. For instance, it can be caused by neighboring WLANs or WPANs. Another problem is that this scheme requires significant changes to the existing IEEE 802.11 standards.

(d) WRAN & 802.11af. The power asymmetry problem between high-power WRAN and low-power IEEE 802.11af devices is studied in [152]. To enhance fair spectrum access between the two networks, the authors develop a low-power reservation scheme that allows low-power 802.11af devices to reserve dedicated time interval from WRAN devices. More specifically, a special preamble is used by 802.11af devices to signal the start of a low-power reservation slot. After detecting the preamble, all nodes must refrain their transmissions for the reserved time interval. The trade-off of choosing the length of the preamble is that too short preamble length results in packet losses at the low-power devices while too long preamble length hampers spatial reuse. Hence, an efficient preamble length selection scheme is devised in this work. Although this scheme requires certain agreement between the two networks to realize fairness, no information exchange is required in the spectrum sharing method, and thus it belongs to uncoordinated schemes.

The power asymmetry problem is tackled in [153] using a cross-layer design of an adaptive Direct-Sequence Spread Spectrum (DSSS) code modulation scheme. The essential idea of the scheme is that a DSSS transmitter spreads a data symbol's energy over a sequence of *N* samples, called a code. The receiver aggregates the energy through matched filtering, which can theoretically improve the link SNR by *N* times. In addition, a traffic-aware code assignment algorithm is proposed for uplink packets to balance the requirements of throughput-intensive and delay-sensitive data traffics. Moreover, to validate the proposed spectrum sharing method, the authors prototyped adaptive DSSS on a TVWS band software radio platform that operates on a spectrum with the FCC-granted experimental license. Experimental results show the high efficiency of the scheme. One problem with this method is that it requires significant changes to existing standards, even though it is implemented in an uncoordinated manner.

The power asymmetry problem in the TVWS band is also studied in [154]. Although the paper focuses on the coexistence of a WRAN and a low-power vehicular network operating in the TVWS band, the proposed spectrum sharing method is so general that it also applies to the coexistence of WRAN and 802.11af networks. The fundamental idea underlying this paper is that, as an add-on to the high-power WRAN, the low-power vehicular network tries to coexist with a WRAN through its own resource allocation based on existing upstream scheduling information that is periodically broadcasted by the base station of the WRAN. Therefore, the coexistence framework require no information exchange or explicit coordination between the WRAN and the vehicular network, which makes it more relevant to implement. More importantly, the vehicular network is not “unrelated” to the WRAN because the vehicular network is also granted to utilize the same unlicensed TVWS band with the WRAN. Since ignoring each other can harm the communication performance of both networks, they all have the intention to create a more friendly coexistence environment.

In this paper, the 802.22-vehicular coexistence problem is formulated as an optimization problem with the objective of maximizing throughput of the vehicular network, subject to the constraint that interference at WRAN CPEs must be less than predefined thresholds. The problem is shown to be an NP-hard mixed-integer nonlinear programing problem, to which the authors develop both a near-optimal algorithm and an efficient approximation algorithm with theoretical guarantees.

Table 5
Examples of the coexistence of hybrid networks.

Coexistence scenarios	Coordinated methods	Uncoordinated methods
ISM band	[60,155]	[156]
TVWS band	[56,157–159]	[160,161]
Others	[162–165]	[13,77]

5.3. Comparison between coordinated and uncoordinated methods

In the previous two parts, we have investigated coordinated and uncoordinated methods for the coexistence of heterogeneous networks, respectively. In addition to the pros and cons enumerated in Table 2, we study more specific differences between these methods in terms of enabling coexistence of two heterogeneous networks.

From the above analysis, we can conclude that uncoordinated methods are more appropriate for the coexistence of homogeneous networks. The reason is that coordinated methods usually require changes to the standards used by coexisting wireless systems (e.g., the aforementioned [140,142,143]), which can be impossible. The reason is that a specific spectrum sharing method between two networks must consider properties of the two networks. Therefore, for any type of network *A*, adding coexistence support for another network *B* results in an amendment to the standard of *A*. However, since network *A* can coexist with many types of networks, it is almost impossible to add coexistence supports for all these networks to its standard. For example, vehicular networks can coexist with WRAN, IEEE 802.22 networks, cellular and many other types of networks in the TVWS band. It is impractical to modify the standard for vehicular communications to accommodate the coexistence with all the aforementioned networks.

In addition, for uncoordinated methods, small-scale or low-power networks (e.g., ad hoc network in [137], WPAN in [42], and IEEE 802.11af network in [152]) should adjust their own transmissions to better coexist with large-scale or high-power networks (e.g., cellular network in [137], WLAN in [42], and WRAN in [152]). The first reason is that the adjustment of large-scale networks can affect many other small-scale networks, which makes the coexistence problem more complicated. The second reason is that the cost of adjusting transmissions can be negligible in small-scale networks while the cost can be fairly high in large-scale networks. Therefore, uncoordinated methods at small-scale networks are more appropriate for the coexistence of heterogeneous networks.

6. Coexistence of multiple hybrid networks

In this section, we investigate the coexistence of multiple homogeneous and multiple heterogeneous networks in the same frequency band. In this case, each network needs to not only consider sharing the band with neighboring homogeneous networks but also consider its coexistence with other heterogeneous networks. Therefore, corresponding spectrum methods must be able to satisfy both of the coexistence requirements. Most of these methods do not rely on PHY/MAC techniques of coexisting networks. Some examples and spectrum sharing methods are provided in Table 5. In the following, we discuss these coordinated and uncoordinated spectrum sharing methods, respectively.

6.1. Coordinated methods for hybrid networks

Since hybrid coexisting networks can use different PHY/MAC techniques, coordinated spectrum sharing methods usually achieve better spectral usage efficiency. However, they also incur additional coordination overhead. Below are some examples of coordinated spectrum sharing methods.

(a) Coexist in the ISM band. In [155], the authors study the coexistence between IEEE 802.15.4g smart utility networks (SUNs) and other homogeneous and heterogeneous networks in the ISM band. SUNs are faced with complicated coexistence environment. Specifically, each SUN not only coexists with other SUNs but also shares the same band with other heterogeneous networks such as IEEE 802.11 b/g/n and IEEE 802.15.1/3/4/4c/4d networks. Three alternative physical (PHY) layer designs have been specified in the 802.15.4g standard, namely multi-rate frequency shift keying, the multi-rate orthogonal frequency division multiplexing and the multi-rate offset quadrature phase shift keying.

A Multi-PHY Management (MPM) scheme is proposed in [155] to facilitate both homogeneous and heterogeneous spectrum sharing for SUNs. The MPM scheme is a control channel-based method discussed in Section 3. The coordination among multiple SUNs is realized through the use of a Common Signaling Mode (CSM) where the Network Coordinator (NC) of a currently operating SUN broadcasts Enhanced Beacons (EBs) periodically. NC of a newly started SUN first senses the channel to discover neighboring networks. If EBs are received, the NC knows that another SUN is operating on the channel, and it either switches to another channel or synchronizes with the operating SUN and waits until the channel becomes available.

Coexistence between an SUN and other heterogeneous networks is enabled through a so-called neighbor network capacity scheme. In a beacon-enabled network, users request Guaranteed Time Slot (GTS) from the NC to perform guaranteed transmission. Moreover, users from neighboring heterogeneous networks are also allowed to request GTS from the NC. If there are still inactive intervals (unassigned GTS) in the SUN, the NC can allocate these intervals to users from the heterogeneous networks. One problem with this method is that interaction between coexisting networks is not studied explicitly, and the coexistence solution is a simple heuristic.

A spectrum etiquette protocol is developed in [60] to enable spectrum sharing among multiple different wireless networks such as WLANs, Zigbee and Bluetooth networks. The fundamental idea of the protocol is to use a common spectrum coordination channel for coexisting networks to announce their transmission parameters. One remarkable advantage of this protocol is that it is “policy neutral” in the sense that it provides a general mechanism, which can accommodate a wide range of specific spectrum sharing rules. Two potential spectrum sharing policies are discussed in this work, namely priority-based and dynamic pricing-based policies. In the first policy, users contend for the same channel based on their data type. In the second policy, when the channel is congested, each user offers to pay a price for accessing spectrum resources, and the winner of the auction proceeds to transmit. Although the authors do not provide specific spectrum sharing rules, they provide details on practical protocol design (e.g., MAC layer details) as well as proof-of-concept experiments to validate the proposed protocol.

(b) Coexistence in the TVWS band. To coordinate spectrum sharing among multiple diverse RF systems, a centralized management framework seems more practical and efficient. For example, a standard-independent coexistence framework was proposed in IEEE 802.19.1 [56] for the coexistence of heterogeneous secondary networks (SNs) in the TVWS band. Moreover, in addition to the TVWS band heterogeneous networks, the standard group is also studying supporting other networks operating in unlicensed bands (e.g., LTE-unlicensed and Wi-Fi) in its recent proposal [56]. Here “standard-independent” means that the coexistence mechanism is not affected by the PHY/MAC standards that SNs follow.

As shown in Fig. 7, in the IEEE 802.19.1 coexistence framework, the coexistence manager (CM), coexistence discovery and information server (CDIS), and coexistence enabler (CE) are the three basic

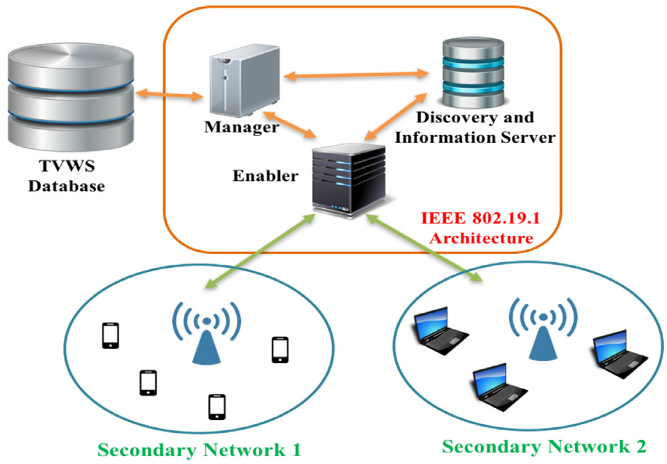

Fig. 7. IEEE 802.19.1 coexistence enabling system.

entities. CM makes coexistence-related decisions, including generating and providing corresponding coexistence requests/commands and control information to the CE. CE facilitates communications between CM and TV band devices. CDIS provides coexistence-related information to CM and is responsible for discovering CEs. The advantage of this framework is the guarantee of reliable and efficient coexistence of heterogeneous SNs. Given this infrastructure framework, more advanced spectrum sharing methods can be developed such as the decision-making algorithm proposed in [157]. However, these solutions are expensive to implement since they require the construction of a large number of management devices. Moreover, overhead and the latency of these methods can be fairly high due to the large amount of information exchange required between coexisting networks and the three coexistence entities, as well as information exchange among coexistence components.

The spectrum allocation algorithm developed in [166] can be leveraged by the IEEE 802.19.1 to allocate available TVWS channels to many hybrid networks with different QoS requirements. In this work, the authors first characterize the theoretical time of a SU using the spectrum depending on its required QoS. Then, a spectrum allocation algorithm for SUs with these different QoS demands is developed considering the mutual interference among the SUs. Although the algorithm is dedicated to the sharing of spectrum among multiple SUs with different Qos demands, it can be incorporated in IEEE 802.19.1 to facilitate the coexistence of multiple secondary networks, in which the coexisting secondary networks have different QoS requirements.

A very similar infrastructure-based spectrum sharing framework is proposed in [159], in which Authorized Geo-location Database (AGDB), Database of Spectrum Usage (DBSU), and Network Management Entity (NME) are used to enable the coexistence of multiple networks operating in the TVWS band. Specifically, Access Point (AP) of an SU first registers its spectrum usage at the DBSU. Before initiating its network, AP of a new SU network must send its geo-location information to the AGDB. The AGDB identifies an available spectrum and returns SU transmission parameters in order to meet the interference constraints at the PU receiver. Then, the new AP provides NME with transmission parameters as well as the quality of transmission that its SU network can achieve. By checking the DBSU, the NME discovers the first SU network in the same spectrum. Subsequently, the NME generates a coexistence solution and returns transmission parameters to the two APs.

Another coordinated spectrum sharing framework is devised in [158] to facilitate the existence of multiple networks operating in the TVWS band. The standard-independent framework enables the exchange of coexistence-related information among coexisting networks in two schemes: centralized (use control infrastructure) and distributed (use control channel). Both schemes require the use of multi-radio cluster-head equipment (CHE) as a physical entity that acquires coexistence-related information, identifies coexistence opportunities, and implements autonomous coexistence decisions. In particular, the authors devise detailed flowcharts for both the two schemes, which illustrates the explicit exchange of coexistence-related information. In the spectrum sharing decision block, dynamic frequency selection and transmit power control are two default spectrum sharing techniques.

(c) Others. Instead of accommodating a specific frequency band, some spectrum sharing methods have been proposed for general coexistence scenarios. For example, in [162], the authors consider the problem of many incompatible wireless devices coexisting in unlicensed bands. Instead of proposing a distinct MAC protocol for each type of application, the authors propose a family of parameterized MAC protocols called WiFlex. Different from most works investigated in this survey, the authors do not consider potential methods to facilitate spectrum sharing between commercially available technologies such as IEEE 802.11, Zigbee and Bluetooth. Instead, they aim to design a flexible common platform that simultaneously supports the communication and coexistence of future high-end and low-end devices. Since all coexisting devices are assumed to use similar PHY/MAC techniques, the inter-network spectrum sharing problem is converted to an intra-network multi-channel medium access control problem.

The authors resolve the conventional multi-channel hidden-node problem and control-channel bottleneck problem using a three-phase asynchronous split phase protocol. Moreover, a control channel-based method is presented to ensure fairness. The method takes advantage of an “overriding” mechanism, in which coexisting devices cooperate to share the same frequency band based on their traffic demands and QoS requirements. Given its flexibility and efficiency in spectrum sharing, this paper is more appropriate for intra-network medium access control instead of current inter-system spectrum sharing since most RF systems are still using their own dedicated PHY/MAC techniques.

Another control channel-based method is proposed in [163] to enable spectrum sharing between two licensed networks (e.g., WiMAX and cellular networks). The essential idea under this method is the so-called “spectrum rental” which shares some similarities with the CR technology. Each licensed network reserves some of its allocated channels for self-usage and opens the remaining channels for rental in order to obtain extra profits. The number of reserved channels depends on its regular traffic loads and QoS requirements. Similar to CR, each network still maintains ownership and first-access priority over the channels for rental. The spectrum rental is implemented using a control channel, on which coexisting licensed networks request/offer channels to each other.

A spectrum load smoothing (SLS) approach is proposed in [164] to meet QoS requirements of coexisting devices. According to this approach, devices try to achieve an equalized load level by redistributing their allocations. More specifically, devices with less restrictive QoS requirements (e.g., less strict delay requirement) distribute their allocated slots to the end of an MAC frame, while devices with more restrictive QoS requirements place their transmissions at the beginning of the current MAC frame. This idea comes from enhanced distributed controlled access scheme in IEEE 802.11e in which QoS provisioning for different applications is supported using different numbers of back-off slots. An important advantage of SLS is that spectrum resources are allocated on a demand basis.

Game theoretical models have been extensively used to facilitate spectrum sharing among multiple networks. An auction-based spectrum sharing method is proposed in [165], subject to a constraint on the interference temperature at a measurement point. Users access the channel using spread spectrum signaling, and thus can cause interference to each other. Each user receives a certain utility as a function of the received SINR. The authors propose two auction mechanisms to allocate the received power. In the first mechanism, users are charged for received SINR, which results in a weighted max-min fair SINR allocation when combined with logarithmic utilities. In the second mechanism, users are charged for transmitting power, which can maximize the total utility when bandwidth is large enough and the receivers are co-located. Both auction mechanisms are proved to be socially optimal for a limiting "large system" with co-located receivers, where bandwidth, power, and the number of users are increased in fixed proportion. Furthermore, the authors propose an iterative and distributed bid-updating algorithm, and specify conditions under which this algorithm converges globally to the Nash equilibrium of the auction.

6.2. Uncoordinated methods for hybrid networks

In this part, we consider the spectrum sharing methods that do not require information exchange and specific coordination among coexisting networks. Instead, each network tries to coexist with others by observing activities on the channel and adjusting its own spectrum access strategies.

(a) Coexist in the ISM band. Although many uncoordinated spectrum sharing mechanisms have been proposed for the coexistence of hybrid networks in the ISM band, most of them focus on either the coexistence of two heterogeneous networks (e.g., WLAN & WPAN and WLAN & Bluetooth networks discussed in Section 5) or coordinated methods discussed above. In contrast, only a few works study uncoordinated methods to enable the coexistence of multiple hybrid networks. For example, in [156], a hybrid direct-sequence (DS) and frequency-hopping (FH) spread spectrum system with beamforming technique is proposed to enable spectrum sharing in the ISM band. Firstly, the FH technique helps coexisting networks avoid causing harmful interference to other networks. Secondly, extra interference reduction can be achieved due to the DS spreading gain.

(b) Coexist in the TVWS band. In [160], the authors propose an uncoordinated spectrum sharing method for secondary networks operating in the TVWS band. They show that if all transmitters use the same power detection threshold and transmit power, coexistence can be achieved in the sense that all active receivers within a certain distance to the transmitters are guaranteed a minimum SINR. More importantly, no information exchange is required in the proposed power control rules, and yet all the coexisting networks can share the same band in a fair and efficient way. We can see that this method is not practical for the coexistence of all networks in TVWS because of the aforementioned power-asymmetry policy regulated by FCC. Specifically, fixed devices can use up to 4 W power while portable devices' transmit power cannot exceed 100 mW. However, this method can apply to the coexistence of networks with similar transmit power levels, e.g., a couple of high-power networks, or several low-power networks.

The problem of mitigating interference among multiple heterogeneous and independently operated secondary networks is investigated in [161] through optimal distributed channel selection. More specifically, the TVWS channel selection process in an arbitrary secondary network is modeled by a decision process, where reward is represented by data rate achievable on a channel and cost is represented by communication overhead for assessing the coexistence interference. Then, by assuming that interference on the available TVWS channels is identically distributed, the channel selection problem is converted from an NP-hard problem to a polynomial-time problem. Finally, an optimal strategy is obtained by solving the polynomial-time problem. Although this method requires little information exchange, it does not apply to secondary networks without central nodes, e.g., vehicular networks.

(c) Others. In [77], the authors propose a distributed spectrum management architecture to deal with spectrum sharing among multiple RF systems (e.g., WiMAX and Wi-Fi), in which nodes share spectrum resource by following several spectrum sharing rules. This method belongs to the uncoordinated sharing rule-based methods discussed in Section 3. The authors formulate the spectrum sharing problem as a constrained channel allocation problem. Five spectrum rules are presented to regulate node behaviors with the objective of maximizing spectrum utilization, which is defined as a proportional fairness function.

The fundamental idea behind the proposed rules is that every coexisting network maintains at least a minimum number of operating channels (i.e., the so-called "poverty line") to guarantee its normal transmission, which eventually leads to fair spectrum sharing among coexisting networks. As an example, in the coexistence scenario studied in this paper where 40 WLAN and WiMAX access points share 20 channels, the poverty line is between 1 and 10. If the number of available channels in a network is less than the poverty line, the network is allowed to "grab" more channels from other neighboring networks. On the other hand, if the number of available channels in the network is greater than its poverty line, this network releases some of the channels to neighboring networks. Moreover, two coexistence scenarios are considered in the paper: conflict free channel assignment and contention-based channel assignment, for which distributed specific sharing rules are proposed.

Similarly, the authors of [13] concentrate on designing self-enforcing rules to achieve efficient, fair, and incentive-compatible spectrum sharing among multiple RF systems through both non-cooperative static and dynamic games. In this context, "efficient" means that it is impossible to improve an individual system's performance without violating other systems' performance; "fair" denotes methods that optimize certain predefined fairness function; and "incentive-compatible" (or "self-enforcing") means that no individual system has any incentive to deviate from the current resource allocation (i.e., every self-enforcing protocol corresponds to a Nash Equilibrium of a game). The authors first characterize the achievable transmission rate region for the case where coexisting systems cooperate with each other, which serves as an upper bond for non-cooperative scenarios. Then, the achievable rate region is studied for the non-cooperative scenarios through both static and dynamic games. In particular, the authors consider potential selfish behaviors of certain coexisting system. A new game is formulated to incorporate the selfish behaviors, and it is proved that this game has an efficient and fair Nash Equilibrium for many fairness functions.

6.3. Comparison between coordinated and uncoordinated methods

In the previous two parts, we have reviewed various coordinated and uncoordinated methods for the coexistence of hybrid networks, respectively. In addition to the pros and cons enumerated in Table 2, we continue to study more specific differences between these methods in terms of enabling coexistence of hybrid networks.

From the above analysis, we can conclude that standard-independent coordinated methods (e.g., [56,159]) are more appropriate for the coexistence of hybrid networks. Firstly, the coexistence of hybrid networks is a combination of homogeneous and heterogeneous coexistence discussed in Sections 4 and 5. In other words, a network has to overcome potential interference from both neighboring homogeneous networks and heterogeneous networks. Therefore, neither simple MAC layer self-coexistence coordinated methods (e.g., [106,117–119,135]) nor uncoordinated methods (e.g., [156,160,161]) can overcome interference from both sources.

Due to their standard-independent property, coordinated methods like IEEE 802.19.1 [56] can easily eliminate mutual interference among hybrid networks. The reason is that these methods are not affected by the PHY/MAC properties of coexisting networks. Instead, all the networks are treated equally as coexisting units seeking for spectrum access. After collecting the requests from the hybrid networks, a central spectrum manager coordinates the transmissions of these units such that they would not cause harmful interference to each other. More importantly, since the standard-independent methods use separate coexistence entities, they require few changes to the wireless standards used by coexisting hybrid networks, which saves a large amount of cost.

7. Coexistence of communication and non-communication systems

In this section, we consider vertical spectrum sharing between a communication system and a non-communication system. Specifically, we study coexistence of radar systems and communication systems. The following reasons explain why we particularly choose radar-communication spectrum sharing as our main example for vertical spectrum sharing. Firstly, radar and communication systems jointly consume most of the highly desirable frequency bands below 6 GHz, and both systems are faced with growing spectrum congestion problem [4]. Hence, efficient spectrum sharing methods can improve the capacities of both types of systems. Secondly, many studies have shown that the underutilized radar spectrum can be used in communication systems to alleviate the spectrum scarcity problem [185,186]. Thirdly, despite its great importance, the study of efficient and practical radar-communication spectrum sharing mechanisms is still at a very early stage.

Most of the existing works on the coexistence of radar and communication systems focus on physical layer issues such as joint waveform and OFDM modulation design [187–190], [191]. Among the few research projects targeting higher layers, SSPARC program supported by DARPA targets the design of spectrum sharing mechanisms to improve radar and communication joint operational capabilities [4] in the S-band (2 GHz–4 GHz). The SSPARC program started in 2013 with the objective of supporting two types of spectrum sharing: spectrum sharing between military radars and military communications systems ("military–military sharing") and spectrum sharing between military radars and commercial communications systems ("military–commercial sharing"). The objective of the military/military sharing is to increase the capabilities of both radar and communication systems simultaneously in congested and contested spectral environments. The military–commercial sharing aims to preserve the radar capabilities while meeting national and international demands for increased commercial communications spectrum, without incurring the high cost of relocating radar systems to new frequency bands.

Next, we discuss coordinated and uncoordinated methods enabling the coexistence of a radar and a communication system. In particular, a comparison of these methods is presented in Table 6.

7.1. Coordinated methods for the coexistence of communication and non-communication systems

In this part, we consider the case where coexisting radar and communication systems are able to exchange a certain amount of information for the coordination of spectrum access.

- *Location information-based coexistence schemes:* One category of coordinated methods assume that radar and communication systems are able to exchange location information to enable better utilization of spectrum resources. For example, a location-aware spectrum and power allocation scheme is proposed in [167] for joint cognitive communication–radar networks. More specifically, location information of the communication system is used by the radar system for adjustable waveform design, target state estimation, and power allocation. In contrast, location information of the radar system is used by the communication system to identify spectrum holes more accurately. Although it may not be possible to acquire location information from the radar systems in practice, this work showcases the benefits of such information exchange for both systems.
- *Interference cancellation-based coexistence schemes:* The fundamental idea under interference cancellation-based schemes is that radars are allowed to demodulate interfering communication signals such that the radars are able to subtract these signals from the received signals [168–170]. For example, in [168], two interference cancellation-based methods are presented (i.e., serial and selective interference cancellation). In the serial cancellation method, a cross-correlation function is used to distinguish reliable signals from interference signals. However, one disadvantage of this method is that the amplitude attenuation and phase rotation of the signals with the same time delay cannot be distinguished through correlation. In contrast, the selective cancellation method only identifies the strongest interference signal. Finally, experiment results show that the selective cancellation method is superior to the serial cancellation method in terms of resulting radar dynamic range and processing time.
- *Joint resource allocation:* In systems where radar imaging and communications are integrated into the same hardware [192–194], joint resource allocation schemes can leverage the integration such that the spectrum usage efficiency is maximized. For example, the joint automotive radar and communication (JARC) system is studied in [171], in which radar imaging and vehicular communications are performed through the same antenna phase array in the 79 GHz mm wave band. In this work, it is shown that exchange of radar imaging results between vehicles through vehicle-to-vehicle communications can improve the individual radar imaging accuracy. Moreover, a centralized joint resource allocation framework is proposed where radar imaging and vehicular communications share the same frequency band in a TDMA manner. Specifically, using the radar imaging accuracy in a pure automotive radar network as a benchmark, the proposed resource allocation algorithm maximizes the left time (i.e., the communication time not dedicated to the exchange of radar imaging results) for other vehicular communications after the benchmark accuracy is achieved.

7.2. Uncoordinated methods for the coexistence of communication and non-communication systems

Compared with coordinated methods, uncoordinated methods are more practical for communication–radar coexistence because it may be impossible to require explicit cooperation from radars, especially for military radars. Similar to CR, in uncoordinated methods, communication systems are required to sense radar signals, and access the spectrum on the condition that they would not cause harmful interference to radar systems. For example, a cooperative sensing algorithm is proposed in [195] to facilitate radar–communication coexistence. The proposed sensing algorithm is able to increase detection range, improve detection probability, and have lower complexity than single terminal sensing.

Table 6
Spectrum sharing methods for communication–radar coexistence.

Methods	Coordination	Examples	Pros	Cons
Location-based methods	Coordinated	[167]	High spatial spectrum usage efficiency, no mutual interference, fair spectrum sharing	Exchange of sensitive location information, signaling overhead
Interference cancellation methods	Coordinated	[168–170]	Normal radar and communication activities not affected, no coordination operations in communication systems,	Sharing of parameters in the communication systems, radar systems need to adjust their activities, signaling overhead
Joint resource allocation	Coordinated	[171]	Optimal spectrum utilization, higher radar imaging accuracy, radar imaging helps vehicles identify neighbors and establish links	Signaling overhead due to the use of centralized control framework
Cognitive radio	Uncoordinated	[172,173]	Protection of radar systems, high spectrum reuse efficiency, no information exchange	Sensing overhead in the communication systems, risk of collision with radar activities
Resource allocation	Uncoordinated	[174,175]	Optimal spectrum usage efficiency, no information exchange	Spectrum sensing overhead, possible computing power requirement, sensing errors
Null space projection	Uncoordinated	[176–180]	No mutual interference, communication activities are not affected	Radar systems adjust their activities, pre-knowledge of communication system
Waveform design-based methods	Uncoordinated	[181–184]	Few coordination operations in communication systems, high spatial spectral efficiency	Significant changes to radar systems, pre-knowledge of communication system

7.2.1. Cognitive radio-based coexistence schemes

One straightforward generalization of the radar–communication coexistence is the PU–SU coexistence defined for the CR technology. Hence, most CR techniques can be converted to facilitate the coexistence of radar and communication systems. In [172], the authors consider opportunistic primary–secondary spectrum sharing when the primary user is a rotating radar. A secondary device is allowed to transmit when its resulting interference will not exceed tolerable interference level of the radar, in contrast to current approaches that prohibit secondary transmissions if radar signals are detected at any time.

They consider the case where an OFDMA-based secondary system operates in non-contiguous cells, which might occur with a broadband hot-spot service, or a cellular system sharing spectrum with a radar system. It is shown that even when an SU is fairly close to a radar, it can still achieve a satisfying communication throughput, albeit with some fluctuations and interruptions as the radar rotates. For example, at 27 percent of the distance at which secondary transmissions will not affect the performance of the radar, the achievable throughput of the SU in down-links and uplinks are around 100 percent and 63 percent respectively of what can be achieved in a dedicated spectrum. Moreover, the authors show that a lot of secondary transmissions are still possible even at different values of key system parameters, such as cell radius, transmit power, tolerable interference level, and radar rotating period. By evaluating a quality of service, it is shown that spectrum shared with radar systems could be used efficiently for communication applications, such as non-interactive video, peer-to-peer file sharing, file transfers, automatic meter reading, and web browsing, but not for delay-sensitive applications such as real-time transfers of small files and VoIP.

A similar scheme is proposed in [173]. The authors propose a novel integrated approach for CR environment with radar signals as PUs. The approach consists of a spectrum sensing technique for radar signals through a Wigner–Hough transformation process, and a dynamic spectrum allocation scheme using multi-objective genetic algorithm. The Wigner–Hough transformation denotes Hough transform of the Wigner–Ville distribution of the signals used on the analysis of multi-component linear-frequency modulation signals, which has been shown to be asymptotically efficient and offers a good rejection capability of the cross terms [196]. The objective is to minimize the interference to radars when they are operating and maximize the spectral efficiency when a radar signal is not detected. In addition, the power consumption of SUs is also considered. For validation, existing methods for the coexistence of a communication system with a radar system are compared in terms of throughput.

7.2.2. Resource allocation-based coexistence schemes

An even more general idea is to enable the radar–communication coexistence via resource allocation within the communication system, e.g., maximizing spectrum efficiency subject to interference constraint on the radar system. In [174], the feasibility of sharing spectrum between cellular systems and stationary radars is studied. This approach allocates resources to mobile devices such that the QoS requirements of mobile applications are met. The rate allocation problem is formulated as two convex optimization problems, where the radar-interfering sector assignments are extracted from the portion of the spectrum non-overlapping with the radar operating frequency. Another resource allocation algorithm with carrier aggregation is proposed in [175] to facilitate coexistence of LTE Advanced cellular systems and S-band radar systems. In particular, the proposed algorithm gives priority to users with inelastic traffic.

7.2.3. Null space projection-based coexistence schemes

The basic idea under one category of uncoordinated methods is to project the radar signals to the null space of the communication system. Such methods are also termed “spatial spectrum sharing” [176]. In [177], the authors consider spectrum sharing between a communication system and an MIMO radar system. They first derive a zero-forcing pre-coder to eliminate radar interference at communication receivers. Then they show that this precoder is equivalent to orthogonal projection matrix onto the null space of an effective interference channel, and choice of pre-coder will degrade target direction estimation performance of the radar. Furthermore, they point out that the radar performance can be improved at the cost of non-zero interference at communication receivers, by projecting the radar signal onto null space of the communication system. Finally, two approaches are proposed to smoothly expand the projected subspace and study the trade-off between radar performance and interference at the communication users.

A blind null-space learning scheme is proposed in [178] for the spatial coexistence of an MIMO communication system and a radar system. One significant difference is that this scheme requires primary users (i.e., radars) to adjust their power such that their transmit power level is a monotonic function of the interference from by the communication system. In [176], a coexistence of maritime radar with a communication system is considered. In this work, the interference channel between the radar and communication system is assumed to be time-varying due to many factors like the motion of the ship. More specifically, the uncertainty of the interference-channel-state-information (ICSI) is modeled using the matrix perturbation theory. The authors study the impact of perturbed ICSI on the null space projection algorithm as well as the radar performance. Other similar schemes have been proposed in [179,180] to facilitate the coexistence of a radar system and an LTE cellular system.

7.2.4. Waveform design-based methods

Apart from the null-space projection-based methods, several other waveform design-based methods have been proposed in the literature, e.g., [181–184]. In [181], an information theoretic waveform design algorithm is proposed for multiple-input–multiple-output radars to support coexistence with a communication system. Additionally, a combined mutual information criterion for the joint waveform and power spectrum design is developed in [182] to optimize the performance of the radar and communications systems. The performance is evaluated in terms of the minimum separation distance between the two coexisting systems, under the constraint that SINR requirements in both systems must be satisfied. As a result, large performance gains close to 3.5 dB in the communication system and 1 dB in the radar system are observed compared to the scenario where the waveform with equal power allocation across the frequency bandwidth is used.

Similarly, in [183], the authors study the synthesis of optimized radar waveforms while ensuring spectral compatibility with the overlaid electromagnetic radiators. In this work, cognition provided by a radio environmental map is exploited so as to induce dynamic spectral constraints on the design of radar waveform. A waveform optimization is proposed aiming at improving some radar performances. The original problem is relaxed into a convex optimization problem, and an algorithm is proposed with polynomial computational complexity. Moreover, waveform performance is also studied in terms of trade-off among the achievable signal to interference plus noise ratio, spectral shape, and the resulting auto correlation function.

Another joint communication–radar waveform design approach is proposed in [184] to achieve high-accuracy radar imaging while maintaining high throughput communications. In this paper, the ultra-wide-band (UWB) is chosen to support joint communication–radar waveform design due to its high spatial resolution and immunity to multi-path fading. First, a novel cognitive radar probing strategy is developed to minimize mutual information (defined in information theory) between successive backscatter UWB pulses. Then, a pulse position modulation-based waveform design is proposed to integrate radar and communication signals.

7.3. Comparison between coordinated and uncoordinated methods

In the previous two sections, we have discussed various coordinated and uncoordinated methods for the coexistence of communication and radar systems, respectively. In addition to the pros and cons enumerated in Table 2, we continue to study more specific differences between these methods in terms of enabling coexistence of radar and communication systems.

From the above analysis and the comparison in Table 6, we can conclude that CR technology is the most appropriate method for the coexistence of radar and communication systems. The first reason is that CR technology does not require sharing of radar-related information or changes to the radar systems. Instead, communication systems can discover spectrum holes in the radar systems through harmless spectrum sensing. The second reason is that spectrum sharing between a radar and a communication system usually happens in the radar frequency (e.g., [4,172,173]). In other words, the communication system wants to reuse the frequency band to improve its communication performance as well as the spectrum usage efficiency. Therefore, as the licensed users of the radar frequency bands, the radar systems should have dominant access priority of that band.

8. Open research problems

In this section, we discuss open research problems in existing spectrum sharing methods. Although some of the problems have been studied in the literature for various applications (e.g., energy saving and QoS provision), their application on enabling coexistence of RF systems has not been studied in depth. Moreover, we will not discuss the open problems that have been identified and extensively studied in traditional RF systems such as synchronization among heterogeneous RF systems, communication overhead in coordinated methods, distributed power control, channel quality characterization, and dynamic channel selection etc. Instead, our discussion is focused on the most fundamental and major open research problems in the context of coexistence of multiple RF systems. In the following, we investigate open research problems in coordinated and uncoordinated spectrum sharing methods, respectively.

8.1. Open research problems in coordinated methods

In coordinated spectrum sharing methods, the first step is usually to exchange spectrum usage information among coexisting RF systems or collect the information at a control entity. Then, spectrum sharing decisions are made based on the shared information. Hence, in the following, we discuss open research problems on information exchange and decision-making, respectively.

8.1.1. Information exchange protocols in control channel-based methods

In the control channel-based methods, neighboring RF systems exchange channel usage information on a common control channel (either in-band or out-of-band). However, it is still an open issue for potentially heterogeneous RF systems to explicitly exchange information on the common control channel. More specifically, since coexisting RF systems can use different radios and PHY/MAC techniques, it is still unresolved how they can explicitly exchange information on the same channel. For example, the CSMA/CA mechanism is used in WLANs while OFDMA is used in WRANs in the MAC layer. Hence, when a WLAN and a WRAN share the same frequency band, they cannot communicate on the common control channel without changing MAC layer protocols. Therefore, in addition to their own MAC protocols, a separate MAC protocol (e.g., TDMA) may need to be developed for coexisting RF systems such that they are able to communicate on the control channel.

Another potential issue on the information exchange is that the control channel can become fairly congested when a large number of neighboring RF systems operate in the same band. For example, when multiple cellular networks, WLANs, IEEE 802.11af networks, and WRANs share the same frequency band, and there is only one control channel, the control channel can become congested easily. Therefore, efficient protocols need to be developed to facilitate the information exchange among heterogeneous RF systems and address the potential congestion issue on the control channel. Similar to the IEEE 802.19.1 standard managing spectrum sharing using infrastructure, corresponding protocols need to be developed to regulate the use of the control channel.

8.1.2. Formulation of coexistence problems

Given the shared information, the control entity (in infrastructure-based methods) or coexisting RF systems (in control channel-based methods) need to make spectrum sharing decisions, which depends on the formulation of the coexistence problem. It is almost impossible to formulate a general problem that could apply to all coexistence scenarios. Therefore, a coordinated method must take into consideration properties of coexisting RF systems, find a system-wide objective function as well as related constraints, develop practical spectrum sharing protocols or strategies, and eventually implement the developed protocols or strategies in real coexistence systems. The coexistence problem can be formulated in any combination of time, frequency, space and code domains, and the problem becomes more complicated when other factors like PHY/MAC properties, QoS requirements, and mobility are considered.

It is still an open issue in many coexistence scenarios to formulate and solve the spectrum sharing problems. For example, although the IEEE 802.19.1 standard has developed a centralized spectrum sharing framework to enable the coexistence of heterogeneous RF systems in the TVWS band, it does not include specific spectrum sharing algorithms. Hence, it is still an open issue to formulate the centralized spectrum sharing problem in the TVWS band. To formulate the problem, the control entity needs to first collect various information from coexisting networks such as network type, size, traffic type, and QoS requirements. Then, a spectrum sharing problem can be formulated with an objective function chosen by the control entity subject to all related constraints. Since the objective function can be chosen dynamically by the control entity, many coexistence goals can be achieved, e.g., spectrum usage efficiency and fairness among coexisting RF systems. Finally, as discussed in Section 3, optimization theory, game theory, and other mathematical tools can be used to solve the formulated coexistence problem.

8.2. Open research problems in uncoordinated methods

In uncoordinated methods, an RF system first monitors spectrum usage information in its neighboring RF systems. Then, it makes spectrum sharing decisions based on the monitored information. Hence, in the following, we discuss open research problems on information monitoring and decision making, respectively.

8.2.1. Identify neighboring RF systems

In cognitive radio techniques, spectrum sensing is often used by secondary users to identify primary user activities [197]. Many spectrum sensing techniques have been developed to fulfill the goal, such as energy-based sensing, cyclo-stationary feature-based sensing, compressed sensing, pilot sensing, waveform-based sensing, and radio identification-based sensing [39]. Similarly, in uncoordinated methods, an RF system must be able to identify its neighboring RF systems such that it can devise corresponding spectrum sharing strategies. In cognitive radio techniques, secondary users only need to identify the existence of primary user activities. However, in uncoordinated methods, an RF system can share the same frequency band with multiple hybrid RF systems with the same or different channel access priorities. Hence, it must be able to not only detect the existence of the neighboring systems but also specifically distinguish them.

Despite its importance, it is still an open issue to distinguish neighboring RF systems in many coexistence scenarios. For example, when a WLAN shares the TVWS band with IEEE 802.11af and IEEE 802.22 networks, it must be able to identify the interference signals from these networks such that it can develop corresponding spectrum sharing schemes. In this case, simple energy-based spectrum sensing techniques cannot fulfill the precise identification of various RF systems. Therefore, more advanced PHY and MAC layer methods must be developed to accomplish this goal. For instance, in addition to the aforementioned spectrum sensing techniques, machine learning [31] and reinforcement learning-based techniques [79] can also be used to identify neighboring RF systems.

8.2.2. Fairness among coexisting RF systems

In uncoordinated methods, due to lack of coordination, coexisting RF systems tend to maximize their own utilities by selfishly dominating usage of the shared spectrum sharing resources. However, these selfish behaviors can lead to serious unfairness issues. For example, when a cognitive vehicular network and an IEEE 802.22 network share the same TVWS channel, although they have the same priority to access the channel, IEEE 802.22 devices are allowed to use significantly higher transmit power than vehicular communication devices [154]. Hence, if the IEEE 802.22 devices take advantage of their high transmit power and selfishly occupy the shared channel all the time, the vehicular devices will not be able to use the channel. Moreover, if the vehicular devices also behave selfishly by keeping transmitting with their maximum power, they can also cause harmful interference to neighboring IEEE 802.22 devices. Therefore, behaving selfishly can result in abuse of the shared spectrum, and degrade the spectrum usage efficiency in all coexisting RF systems.

One potential approach to addressing the unfairness issue is to regulate spectrum sharing using predetermined etiquette. More specifically, every RF system must agree to leave some spectrum resources to other neighboring RF systems. However, it is still an open issue how many spectrum resources should be left to other neighboring RF systems. Moreover, the etiquette can lead to waste of the shared spectrum due to lack of information exchange and coordination among the coexisting RF systems. In our example, although the IEEE 802.22 devices have left some channels to vehicular devices, the vehicular devices may have no data to transmit, which results in a waste of the channels. Therefore, more efficient spectrum sharing etiquette should be developed to balance the tradeoff between spectrum usage fairness and efficiency.

8.2.3. Development of sharing rule-based methods

As discussed in Section 3, in a sharing rule-based method, the spectrum sharing problem is first formulated as an uncoordinated spectrum utilization problem with an objective function and multiple system constraints. Then, optimal or sub-optimal solutions can be obtained by solving these problems, which can be further represented by specific uncoordinated spectrum sharing rules. However, the development of such sharing rule-based methods is faced with two significant challenges. The first challenge is the accurate formulation of uncoordinated coexistence problems, and the second challenge is the development of efficient algorithms that must not only solve the coexistence problem, but also obtain specific sharing rules. Due to these challenges, only a few sharing rule-based methods have been proposed in the literature, e.g., [29,77,78]. Therefore, more efforts are needed to develop sharing rule-based methods to facilitate the coexistence of multiple RF systems.

9. Conclusions

In this paper, we investigated techniques and methods in the literature to facilitate spectrum sharing among multiple RF systems. Firstly, we classify existing coexistence scenarios, and explicitly compare our survey with existing books and survey papers on spectrum sharing in Section 2. Secondly, we investigate existing spectrum sharing methods as well as mathematical tools used in these methods in Section 3. Then, for horizontal coexistence scenarios, we discuss the coexistence of homogeneous, heterogeneous and multiple hybrid networks in Sections 4–6, respectively. In particular, we provide specific coexistence examples and analyze spectrum sharing methods used in these examples in depth. For vertical spectrum sharing, we particularly study the radar–communication coexistence in Section 7. Finally, we investigate open research issues on existing spectrum sharing methods and try to provide insights to resolving these issues in Section 8.

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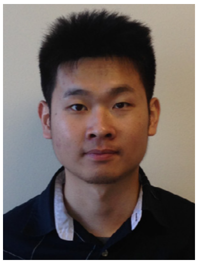

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