Chapter 2
Taxonomy of Coexistence Mechanisms

In the pervious chapter, we identify a few problems that are related to the medium access control (MAC) layer protocol design for coexistence of CR networks. To offer a clear picture of coexistence issues and related technical challenges to these problems, in this chapter, we propose a taxonomy of coexistence mechanisms for CR networks [31]. These background knowledge will facilitate the understanding of the various nomenclature and concepts that will be used throughout the book.

We first briefly review recently published or emerging wireless standards that prescribe license-exempt operation in TVWSs, including those for heterogeneous coexistence [8, 37] that can be applied to homogeneous coexistence scenarios. In December 2009, ECMA-392 [24] was finalized as the first standard for personal/portable CR devices operating in TVWSs. It specifies MAC and PHY operations and defines several self-coexistence mechanisms for inter-network coordination and interference mitigation. In 2008, Google and Microsoft proposed the idea of WiFi-like operation in TVWSs, called WiFi 2.0 or WhiteFi. A new standard based on this idea was formalized as IEEE 802.11af [53], which targets higher rate and wider coverage than the current WiFi services by using CR-enabled access points (APs) and user terminals. Besides incumbent protection, IEEE 802.11af also needs to address the coexistence of co-located APs, even though the coexistence mechanisms are yet to be finalized. License-exempt operation of existing licensed networks, e.g., LTE and IEEE 802.16, further creates new challenges. At present, license-exempt LTE [83] is still in its infancy, but IEEE 802.16h [48] was published as a standard amendment for license-exempt WiMAX in July 2010. In IEEE 802.16h, various coordinated and uncoordinated coexistence mechanisms are proposed, which are suitable for the coexistence of metropolitan area networks with heterogeneous others in TVWSs. In July 2011, IEEE 802.22 [50] was released as a new standard for long-range CR networks located in rural areas using TVWSs. Like ECMA-392, several self-coexistence mechanisms are defined in it to mitigate mutual interference among co-located networks belonging to different operators. Furthermore, IEEE 802.19.1 [8] and COGEU project [77] are being developed to provide general solutions to the coexistence of 802 or non-802 networks in various CR-enabled use cases—e.g., campus, apartment complex, and home. A typical IEEE 802.19.1 system consists of a

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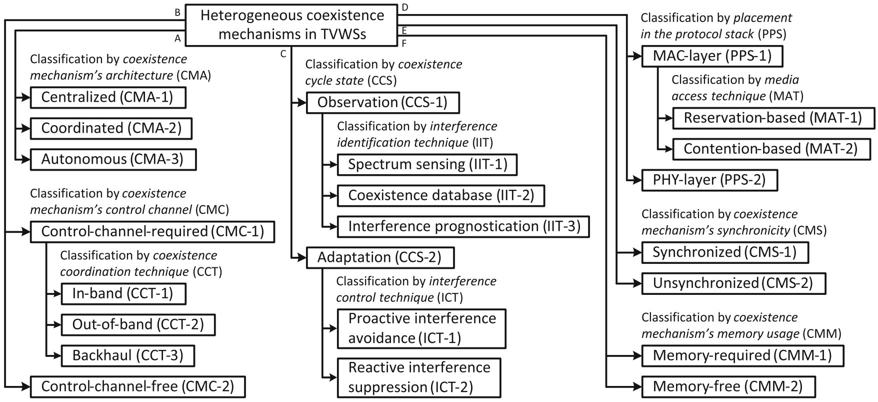

Fig. 2.1 A taxonomy of coexistence mechanisms in TVWSs

coexistence manager, which acts as a centralized resource allocator, and a coexistence enabler, which acts as a coexistence information collector maintaining interfaces between the coexistence enabler and coexisting CR networks. The HC issues are common not only in TVWSs but also in ISM bands. A widely studied coexistence scenario is the co-channel coexistence of low-power IEEE 802.15 networks and high-power IEEE 802.11 networks [81–118]. This problem is also addressed by IEEE 802.15.2. Another popular coexistence scenario is the co-channel coexistence of contention-based IEEE 802.11/802.15 networks and reservation-based IEEE 802.16 networks [57, 71]. The coexistence mechanisms defined in these standards will be introduced as examples in detail.

The proposed taxonomy classifies coexistence mechanisms using a diverse set of criteria as shown in Fig. 2.1. For each category of the taxonomy, we provide examples and discuss the pros and cons of related coexistence mechanisms. In Table 2.1, we map coexistence mechanisms, which have been proposed in the literature or standards, to our taxonomy.

2.1 Classification by Coexistence Mechanism's Architecture (A)

The sharing of TVWSs among coexisting networks can be achieved in several ways depending on whether or not decision-making coexistence infrastructures and inter-network coordination channels are available. Based on the coexistence mechanism's architecture (CMA), coexistence mechanisms are classified into centralized, coordinated, and autonomous categories.

CMA-1: Centralized Mechanisms. Centralized mechanisms require both decision-making coexistence infrastructures and inter-network coordination channels. A coexistence scenario for centralized mechanisms is illustrated in Fig. 2.2a. Each

Table 2.1 Mapping of coexistence mechanisms to classification methods

	CMA-1	CMA-2	CMA-3	CMC-1: CCT-1	CMC-1: CCT-2	CMC-1: CCT-3	CMC-2	CCS-1: IIT-1	CCS-1: IIT-2	CCS-1: IIT-3	CCS-2: ICT-1	CCS-2: ICT-2	PPS-1: MAT-1	PPS-1: MAT-2	PPS-2	CMS-1	CMS-2	CMM-1	CMM-2
Adaptive modulation and coding			✓				✓					✓			✓		✓		✓
Centralized coexistence framework	✓					✓					✓		✓			✓		✓	
Coexistence beacon signaling		✓		✓				✓					✓			✓			✓
Coexistence control channel		✓			✓			✓					✓			✓			✓
Coexistence frame scheduling		✓			✓			✓			✓		✓			✓			✓
Coexistence information database		✓				✓			✓				✓			✓		✓	
Cognitive pilot channel		✓			✓			✓					✓			✓		✓	
Collocated coexistence messaging		✓		✓				✓					✓			✓			✓
Cooperative busy tone signaling		✓		✓				✓						✓			✓		✓
Coordinated contention-based protocol		✓			✓			✓			✓			✓		✓			✓
Credit-token-based coexistence protocol		✓			✓			✓			✓		✓			✓			✓
Dynamic frequency/channel selection			✓				✓	✓			✓		✓				✓	✓	
Interference cancellation and suppression			✓				✓					✓			✓	✓		✓	
Internet-server-facilitated messaging		✓				✓		✓					✓			✓		✓	
Listen before talk			✓				✓	✓			✓			✓			✓		✓
Opportunistic channel access			✓				✓			✓				✓			✓	✓	
Smart antenna			✓				✓					✓			✓		✓		✓
Time/frequency-division multiple access	✓					✓					✓		✓			✓		✓	
Transmit power control			✓				✓					✓			✓		✓		✓

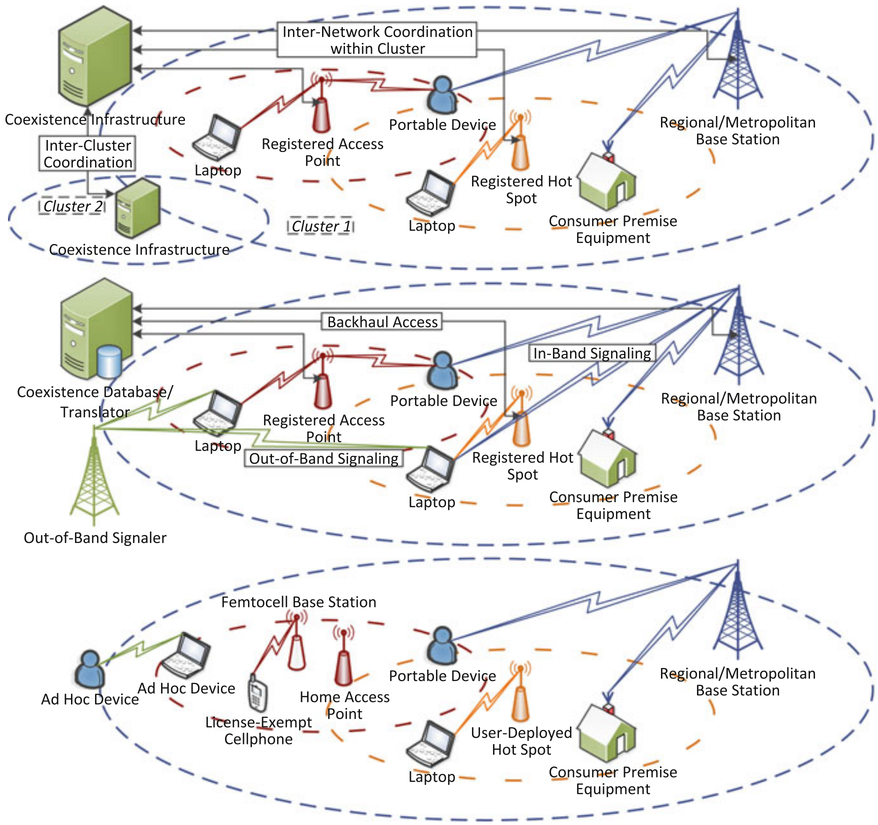

Fig. 2.2 Examples of coexistence scenarios: **a** centralized mechanisms (*top*); **b** Coordinated mechanisms (*middle*); and **c** Autonomous mechanisms (*bottom*)

operator can deploy a single or multiple infrastructures to carry out centralized spectrum sharing via a star-topology or a cluster-based architecture. In each cluster, as in Fig. 2.2a, each coexistence infrastructure minimizes interference among registered coexisting networks based on centrally collected coexistence information. Furthermore, multiple coexistence infrastructures can coordinate with each other for further collaboration. For example, the standard-independent centralized coexistence framework in IEEE 802.19.1 defines a coexistence manager for central management of all associated networks. In addition, the collaboration of multiple 802.19.1 coexistence managers or cluster-head equipments [107] can be supported through certain inter-cluster coordination interfaces. Centralized mechanisms can operate independently of existing wireless standards, and thus, registered networks can be heterogeneous and no major standard modifications are required. They can effectively minimize inter-network interference by utilizing centrally collected global coexistence information. However, centralized solutions incur costly new infrastructures and subsequent operational costs. The effectiveness of centralized mechanisms is diminished when a significant fraction of the coexisting devices/networks are not registered and not under central control.

CMA-2: Coordinated Mechanisms. Coordinated mechanisms are applied when each coexisting network locally conducts resource allocation without the need for extra decision-making coexistence infrastructures but inter-network coordination channels are still available. A coexistence scenario that employs coordinated mechanisms is illustrated in Fig. 2.2b. The coexisting networks coordinate with each other through various information signaling and retrieving techniques. Based on the collected coexistence information, each network can make decisions to mitigate inter-network interference. For example, the cooperative busy tone signaling technique [118] helps high-power IEEE 802.11 networks detect signaling messages from co-channel, low-power IEEE 802.15.4 networks to prevent 802.11 devices from dominating the channel contention process. Coordinated mechanisms achieve effective inter-network interference mitigation. However, they are often limited to certain coexistence scenarios. More details about coordination channels will be discussed in the next subsection.

CMA-3: Autonomous Mechanisms. When neither decision-making coexistence infrastructures nor inter-network coordination channels are available, each coexisting network has to utilize autonomous mechanisms to achieve best-effort interference mitigation. A coexistence scenario for autonomous mechanisms is illustrated in Fig. 2.2c. Each coexisting network performs resource allocation and manages inter-network interference only based on local observation. For example, the dynamic frequency/channel selection technique enables each network to select or switch to the channel with the least amount of interference based on the local evaluation of channel quality. The listen before talk policy prescribes a device to access spectrum based on the outcome of local spectrum sensing. Autonomous mechanisms are low in complexity and can adapt to dynamic environments. They can be integrated with centralized and coordinated mechanisms to build hybrid mechanisms. However, autonomous mechanisms by themselves may not sufficiently mitigate inter-network interference due to their best-effort nature.

2.2 Classification by Coexistence Mechanism's Control Channel (B)

The availability of control channels for inter-network coordination directly determines the design of coexistence mechanisms. Based on the coexistence mechanism's control channel (CMC), coexistence mechanisms are classified into control channel-required and control channel-free categories.

CMC-1: Control Channel-Required Mechanisms. Both centralized mechanisms (CMA-1) and coordinated mechanisms (CMA-2), whose operations necessarily require inter-network coordination, fall into this classification. Based on the coexistence coordination technique (CCT), control channel-required mechanisms are further classified into in-band, out-of-band, and backhaul categories.

CMC-1: CCT-1: In-Band Mechanisms. To deliver coexistence information to coexisting neighbors, each device can periodically broadcast coexistence signaling messages on its data channels, such as in-band signaling illustrated in Fig. 2.2b. For example, the coexistence beacon signaling in ECMA-392 and IEEE 802.22 defines specific time slots in each network's regular superframes for periodic broadcast of coexistence beacons. Although such a technique is used for self-coexistence purpose here, it can be a coexistence mechanism when coexisting networks can decode signaling messages between them. The co-located coexistence messaging technique [29] lets each multi-radio user terminal forward in-band signaling messages among its multiple heterogeneous home networks. In-band mechanisms do not require extra infrastructures or control channels for inter-network coordination. However, they only work when coexisting networks use the same radio access technology or when heterogeneous devices can decode each others' signaling messages.

CMC-1: CCT-2: Out-of-Band Mechanisms. Instead of relying on data channels, coexisting networks can broadcast coexistence signaling messages on a dedicated or dynamically established common control channel, such as out-of-band signaling illustrated in Fig. 2.2b. For example, the coexistence control channel in IEEE 802.16h supports secondary synchronization, user detection, interference evaluation, and inter-system communication. The cognitive pilot channel [37] always carries up-to-date coexistence information, broadcasted by operators or third-party entities, which can be retrieved by each network on demand. Out-of-band mechanisms can be used in direct inter-network negotiations if a standardized signaling message format is adopted. However, they fully rely on the existence and reliability of a common control channel.

CMC-1: CCT-3: Backhaul Mechanisms. When wired backhaul links are available, these links can be used to coordinate spectrum access among the coexisting networks. As shown in Fig. 2.2b, each network can either access a central coexistence database or coordinate with neighbors using the method of message translation. For example, the coexistence information database [8], which is implemented on servers connected to the Internet, provides on-demand lookup functionality. The Internet server-facilitated messaging technique [8] enables inter-network coordination over the Internet by providing message translation and forwarding services. Backhaul mechanisms can provide relatively complete knowledge of the spectrum environment in the vicinity of each network in a short time. They enable active reporting and retrieving of coexistence information instead of passive network detection. However, backhaul links may not cover all the coexisting networks to make coexistence information incomplete.

CMC-2: Control Channel-Free Mechanisms. In the context of our taxonomy, control channel-free mechanisms are classified under a category that is equivalent to the one that autonomous mechanisms (CMA-3) are classified under.

2.3 Classification by Coexistence Cycle State (C)

The simplified cognition cycle of a CR consists of three states: observation, decision, and adaptation [73]. Based on this cycle, we propose a classification of coexistence mechanisms based on the coexistence cycle state (CCS), which includes: observation and adaptation categories.

CCS-1: Observation Mechanisms. The purpose of observation state is to identify the presence or even the source of inter-network interference. Based on the interference identification technique (IIT), observation mechanisms are further classified into spectrum sensing, coexistence database, and interference prognostication categories.

CCS-1: IIT-1: Spectrum Sensing Mechanisms. For the detection of coexisting networks, each CR network can either locally scan TVWSs via spectrum sensing or cooperatively exchange coexistence information with neighbors through inter-network coordination channels. Note that the purpose of spectrum sensing here is to detect coexisting secondary networks instead of primary incumbents. For example, the scanning-based opportunistic channel access technique [81] enables each IEEE 802.15.4 network to scan multiple channels potentially interfered by IEEE 802.11 networks, and keep searching for a better channel selection by using simulated annealing optimization method. The metric of channel quality is computed in terms of the energy of detected 802.11 interference and the number of heard 802.15.4 beacons. The coexistence beacon signaling and coexistence control channel techniques facilitate cooperative spectrum sensing and coexistence information exchange by providing means for in-band or out-of-band inter-network coordination. Spectrum sensing mechanisms are relatively easy to implement. However, they are unreliable in real-world coexistence scenarios, and need to be augmented with other methods for reliable detection of coexisting networks.

CCS-1: IIT-2: Coexistence Database Mechanisms. A coexistence database storing geolocation and operation information about secondary CR networks can be utilized by each coexisting network to help identify potential sources of interference. For example, the coexistence information database in IEEE 802.16h stores the shared information regarding the actual and intended usage of spectrum resource for certain local regions. Besides base stations, user terminals also contribute to complete the database by providing interference information pertinent to themselves. Coexistence database mechanisms provide a more practical and effective means of detecting coexisting networks. However, they cannot detect the presence of unregistered devices/networks at the database authority.

CCS-1: IIT-3: Interference Prognostication Mechanisms. The past spectrum sensing results can help each network make predictions on the availability of spectrum and potential interference. Techniques for interference prognostication include modeling and machine learning. These techniques can be used to predict the behavior of potential interferers by leveraging their past spectrum access behavior. For example, the learning-based opportunistic channel access techniques [46, 81] enable each IEEE 802.15.4 network to learn the statistical regularity of IEEE 802.11 operation and predict the opportunities of white spaces free of 802.11 traffic. The ideas are similar to the modeling of primary users' behavior in order to empirically prevent secondary users from using the same spectrum being occupied by primary users. Interference prognostication mechanisms offer low-power networks more opportunities of spectrum access by circumventing high-power networks. However, their effectiveness highly relies on the accuracy of predictions, which is very challenging to guarantee for the operation in TVWSs.

CCS-2: Adaptation Mechanisms. Once inter-network interference has been detected, a network needs to adapt to its interference environment by taking various measures to change its transmission characteristics. Based on the interference control technique (ICT), adaptation mechanisms are further classified into proactive interference avoidance and reactive interference suppression categories.

CCS-2: ICT-1: Proactive Interference Avoidance Mechanisms. Upon detecting interference from neighbors, each CR network can choose to directly switch to a better-quality channel, if such a channel is available, or wait until the channel becomes vacant. If coordination channels are available, inter-network interference can even be avoided in advance. For example, the dynamic frequency/channel selection technique provides a certain network with a list of candidate channels that can be used for channel switching whenever needed. The time/frequency-division multiple access is a common interference avoidance technique that centrally enables coexisting networks to operate in separate time slots or channels. Proactive interference avoidance mechanisms are suitable for the coexistence of CR networks, since CR devices are capable of dynamic spectrum access. However, they necessarily require the support of observation mechanisms to identify the candidate channels free of interference.

CCS-2: ICT-2: Reactive Interference Suppression Mechanisms. Interference suppression techniques are used to alleviate or suppress interference but do not enable a network to avoid it. For example, the interference cancellation and suppression technique [71] enables a network that is experiencing interference to utilize adaptive filters or prior knowledge of interferers to estimate and cancel the interference step by step. The transmit power control policy can be used to mitigate co-channel or adjacent-channel interference when the coexisting networks are managed by the same operator. Reactive interference suppression mechanisms help to support non-exclusive co-channel spectrum sharing as long as inter-network interference is tolerable. However, their effectiveness is usually limited, especially when interference comes from high-power interferers that belong to different operators.

2.4 Classification by Placement in the Protocol Stack (D)

In general, inter-network interference is mitigated in the MAC or PHY layer of the protocol stack. Based on the placement in the protocol stack (PPS), coexistence mechanisms are classified into MAC-layer and PHY-layer categories.

PPS-1: MAC-Layer Mechanisms. Most coexistence mechanisms are placed in the MAC layer. Medium access can be performed in one of two waysłeach network can choose to either reserve or contend for spectrum resource. Based on the media access technique (MAT), MAC-layer mechanisms are further classified into reservation-based and contention-based categories.

PPS-1: MAT-1: Reservation-Based Mechanisms. Reservation-based spectrum sharing can be achieved in the time, frequency, and space domains (space-division mechanisms are included in the PPS-2 category). In the time domain, multiple co-channel networks can take turns to access the shared channel in separate time frames or slots. For example, the coexistence frame scheduling in IEEE 802.16h divides time frames into Master, Slave, and Shared subframes, which can be scheduled by each base station for uplink and downlink in a flexible mode. The operation of Master systems in their Master subframes should be protected from harmful interference caused by concurrent Slave systems, and coexisting networks equally share the role of Master system on a rotating basis. In Shared subframes, all the coexisting networks may operate in parallel under the limits on transmit power levels. In the frequency domain, multiple coexisting networks can simultaneously access the same TVWSs but use separate channels or subchannels by direct or orthogonal spectrum splitting. Furthermore, time-frequency resource blocks may be conceived for greater flexibility and granularity in spectrum sharing. For example, the credit token-based coexistence protocol in IEEE 802.16h permits auction-based spectrum leasing among coexisting networks for channel reservation in the subsequent time frames. Each network can be either an offerer or a requester to transfer the “ownership” of spectrum dynamically. Reservation-based mechanisms can guarantee fairness and reliable throughput of coexisting networks regardless of the discrepancy in their channel definitions, signal characteristics, or transmit power levels. However, they need to be supported by inter-network coordination channels or even extra coexistence infrastructures.

PPS-1: MAT-2: Contention-Based Mechanisms. Contention-based media access can also be used to support heterogeneous coexistence. For example, the coordinated contention-based protocol in IEEE 802.16h prescribes networks with reservation-based MAC to periodically halt transmissions so that the resulting idle time frames can be utilized by networks with contention-based MAC. Contention-based mechanisms are easy to implement, and do not require strict inter-network synchronization. However, they do not always guarantee fairness and constantly reliable spectrum access due to the randomness of contention results.

PPS-2: PHY-Layer Mechanisms. In the PHY layer, various techniques can be used to mitigate inter-network interference. For example, the smart antennas can be used to reduce the coexistence-related interference by minimizing sidelobe radiation. The spatial reuse of shared spectrum can be improved by directional interference patterns. The adaptive modulation and coding technique enhances coexistence via dynamically adaptable PHY parameters according to the varying radio environments, such as path loss and interference. Most PHY-layer mechanisms also belong to autonomous mechanisms (CMA-3), so further discussion is neglected.

2.5 Classification by Coexistence Mechanism's Synchronicity (E)

The mitigation of inter-network interference can be facilitated by coexistence mechanisms synchronized across coexisting networks. Based on the coexistence mechanism's synchronicity (CMS), coexistence mechanisms are classified into synchronized and unsynchronized categories.

CMS-1: Synchronized Mechanisms. A number of coexistence techniques require accurate inter-network synchronization, at either the MAC or the PHY layer. For example, the coordinated contention-based protocol requires the coexisting networks with reservation-based MAC synchronize their quiet periods so that the carrier sensing of co-channel networks with contention-based MAC can discover such opportunities. The coexistence beacon signaling and coexistence control channel techniques enable faster detection of coexisting networks if the networks synchronize with each other, due to the periodicity of in-band or out-of-band signaling. Synchronized mechanisms address coexistence issues via precise separation of coexisting networks in the time domain. However, inter-network synchronization is difficult to implement without extra infrastructures to support.

CMS-2: Unsynchronized Mechanisms. Inter-network synchronization is not necessary for a number of coexistence techniques. For example, the listen before talk policy enables coexisting networks to contend for spectrum access in an asynchronous manner. The cooperative busy tone signaling technique is proposed as an enhancement of CSMA protocol for IEEE 802.15.4 networks, and does not require synchronization with co-channel IEEE 802.11 networks using CSMA protocol as well. Unsynchronized mechanisms can be readily implemented. However, in most cases, they can only alleviate inter-network interference but cannot avoid it.

2.6 Classification by Coexistence Mechanism's Memory Usage (F)

Certain coexistence mechanisms require the storage of coexistence information. Based on the coexistence mechanism's memory usage (CMM), coexistence mechanisms are classified into memory-required and memory-free categories.

CMM-1: Memory-Required Mechanisms. In some coexistence techniques, memory is needed to store necessary coexistence information. For example, the coexistence information database stores up-to-date geolocation and operation information about secondary CR networks. The machine learning-based opportunistic channel access needs to record recent history of spectrum sensing results and maintain a knowledge base to make reasonable interference predictions. Memory-required mechanisms can help make faster and more thoughtful decisions. However, the costs for memory consumption can be high especially in large-scale complex coexistence scenarios, e.g., an apartment building in a dense urban area.

CMM-2: Memory-Free Mechanisms. A number of coexistence techniques do not require memory usage or only require a negligible size of memory. For example, the co-located coexistence messaging technique for each multi-radio user terminal directly forwards signaling messages from one of its home networks to another one without the need for recording the messages. The cooperative busy tone signaling technique only requires IEEE 802.15.4 signalers to emit busy tones to IEEE 802.11 receivers for spectrum reservation. The listen before talk policy is another typical example. Memory-free mechanisms are suitable for autonomous networks that do not have much system resource. However, their achieved performance in terms of fairness, spectrum utilization, or throughput may not be as good as that by memory-required mechanisms due to limited coexistence knowledge.

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