A TAXONOMY OF COEXISTENCE MECHANISMS FOR HETEROGENEOUS COGNITIVE RADIO NETWORKS OPERATING IN TV WHITE SPACES

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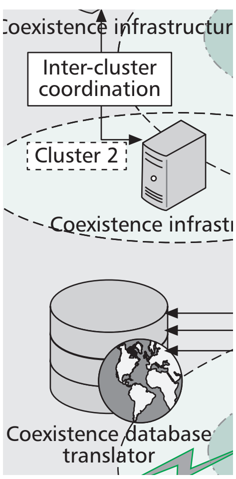

The authors discuss the mechanisms that have been proposed for heterogeneous coexistence, and propose a taxonomy of those mechanisms targeting TVWSs.

ABSTRACT

With the development of dynamic spectrum access technologies, such as cognitive radio, the secondary use of underutilized TV broadcast spectrum has come a step closer to reality. Recently, a number of wireless standards that incorporate CR technology have been finalized or are being developed to standardize systems that will coexist in the same TV white spaces. In these wireless standards, the widely studied problem of primary-secondary network coexistence has been addressed by the use of incumbent geolocation databases augmented with spectrum sensing techniques. However, the challenging problem of secondary-secondary coexistence—in particular, heterogeneous secondary coexistence—has garnered much less attention in the standards and related literature. The coexistence of heterogeneous secondary networks poses challenging problems due to a number of factors, including the disparity of PHY/MAC strategies of the coexisting systems. In this article, we discuss the mechanisms that have been proposed for heterogeneous coexistence, and propose a taxonomy of those mechanisms targeting TVWSs. Through this taxonomy, our aim is to offer a clear picture of the heterogeneous coexistence issues and related technical challenges, and shed light on the possible solution space.

INTRODUCTION

In 2008, the Federal Communications Commission (FCC) authorized license-exempt operation of cognitive radio (CR) devices in TV bands (i.e., VHF/UHF 54–698 MHz) in order to further utilize the fallow spectrum in these bands, which is commonly termed TV white spaces (TVWSs). Due to the desirable signal propagation characteristics in the TV bands and overcrowding in the industrial, scientific, and medical (ISM) bands, a number of emerging standards prescribe wireless access technologies operating in the TVWSs, and more standards are expected to follow suit. These heterogeneous secondary wireless access technologies are expected to coexist in the same TV bands, and this creates the need for heterogeneous coexistence (HC) mechanisms to mitigate harmful mutual interference. Different from HC issues in the ISM bands, the coexistence problem is more complex and challenging in the TVWSs due to the signal propagation characteristics in TV bands, the spectrum agility of systems operating in TVWSs, and the disparity of physical/medium access control (PHY/MAC) strategies of the coexisting systems. The excellent RF penetration depth of signals in TV bands can cause a high level of internetwork interference. The dynamic nature of opportunistic spectrum access makes the problem of coexistence more complex. Furthermore, the heterogeneity of coexisting networks in terms of network architecture, radio access technologies (RATs), and required quality of service (QoS) poses very challenging problems in the design of HC mechanisms.

In the standards and related literature, the widely studied incumbent protection problem (i.e., the coexistence of secondary CR networks and licensed incumbent networks) has been addressed by the use of incumbent geolocation databases augmented with spectrum sensing techniques. However, to date, the problem of secondary-secondary coexistence—especially heterogeneous coexistence—has garnered little attention [1, 2].

Here, we briefly review recently published or emerging wireless standards that prescribe license-exempt operation in TVWSs. In the forthcoming section, the coexistence mechanisms of the proposed taxonomy are discussed in the context of these standards. In December 2009, ECMA-392 [3] 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 internetwork 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 [4], which targets a higher rate and wider coverage than the current WiFi services by

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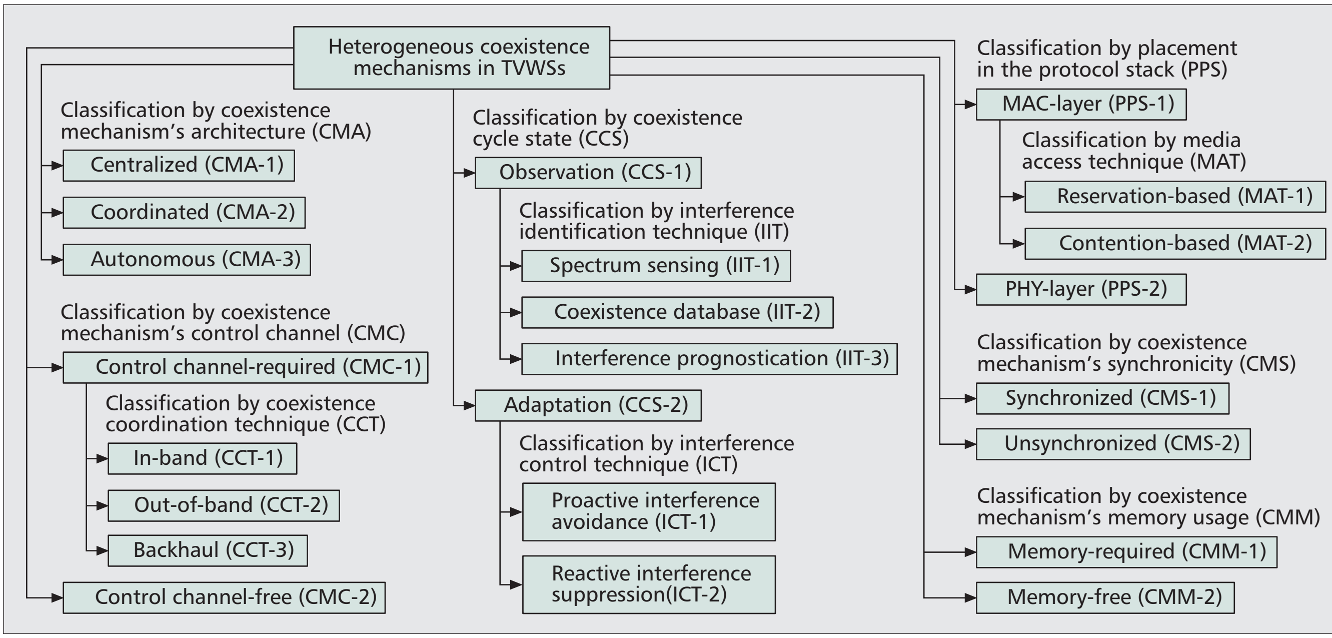

Figure 1. *Taxonomy of HC mechanisms in TVWSs.*

using CR-enabled access points (APs) and user terminals. Besides incumbent protection, IEEE 802.11af also needs to address the coexistence of collocated APs, even though the coexistence mechanisms are yet to be finalized. License-exempt operation of existing licensed networks (e.g., Long Term Evolution [LTE] and IEEE 802.16) further creates new challenges. At present, license-exempt LTE [5] is still in its infancy, but IEEE 802.16h [6] 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 [7] 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 collocated networks belonging to different operators. Furthermore, IEEE 802.19.1 [2] and the COGEU project [8] 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 *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 [11–13]. 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 [15, 16]. The coexistence mechanisms defined in these standards will be introduced as examples in the next section in detail.

In light of the above challenges, in this article, we propose a taxonomy of coexistence mechanisms for heterogeneous CR networks operating in TVWSs. Through this taxonomy, our aim is to offer a clear picture of HC issues and related technical challenges, and, moreover, shed light on the possible solution space.

A Taxonomy of Heterogeneous Coexistence Mechanisms

The proposed taxonomy classifies HC mechanisms using a diverse set of criteria as shown in Fig. 1. For each category of the taxonomy, we provide examples and discuss the pros and cons of related HC mechanisms. Note that some of the mechanisms discussed in the following discussions are not applicable to HC exclusively—they are also applicable to self-coexistence (i.e., coexistence between systems with the same or compatible air interface). In Table 1, we map HC mechanisms that have been proposed in the literature or standards to our taxonomy.

Classification by Coexistence Mechanisms Architecture

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

CMA-1: Centralized Mechanisms — Centralized mechanisms require both decision-making coexistence infrastructures and internetwork coordination channels. A coexistence scenario for

Coexistence mechanism \ Classification method	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 (802.11, LTE, 802.16, 802.22)			Y				Y					Y			Y		Y		Y
Coexistence beacon signaling (ECMA-392, 802.22)		Y		Y				Y					Y			Y			Y
Cooperative busy tone signaling ([13])		Y		Y				Y						Y			Y		Y
Coexistence control channel ([16], 802.16h)		Y			Y			Y					Y			Y			Y
Co-located coexistence messaging ([10], 802.16)		Y		Y				Y					Y			Y			Y
Coordinated contention-based protocol (802.16h)		Y			Y			Y			Y			Y		Y			Y
Coexistence frame scheduling (802.16h)		Y			Y			Y			Y		Y			Y			Y
Coexistence information database ([1, 2], 802.16h)		Y				Y			Y				Y			Y		Y	
Cognitive pilot channel ([1])		Y			Y			Y					Y			Y		Y	
Credit token-based coexistence protocol (802.16h)		Y			Y			Y			Y		Y			Y			Y
Dynamic frequency/channel selection ([2, 5], ECMA-392, 802.16h, 802.22)			Y				Y	Y			Y		Y				Y	Y	
Interference cancellation and suppression ([15], 802.15.2)			Y				Y					Y			Y	Y		Y	
Internet server-facilitated messaging ([2])		Y				Y		Y					Y			Y		Y	
Listen before talk ([2], ECMA-392, 802.11, 802.16h)			Y				Y	Y			Y			Y			Y		Y
Opportunistic channel access ([11, 12, 15])			Y				Y			Y				Y			Y	Y	
Smart antenna ([1, 2], ECMA-392, 802.11, LTE, 802.16, 802.22)			Y				Y					Y			Y		Y		Y
Standard-independent centralized coexistence framework ([2, 8, 9])	Y					Y					Y		Y			Y		Y	
Time-/frequency-division multiple access ([1, 2], 802.15.2)	Y					Y					Y		Y			Y		Y	
Transmit power control ([1, 2, 14], ECMA-392, 802.11, LTE, 802.16, 802.22)			Y				Y					Y			Y		Y		Y

Table 1. *Mapping of HC mechanisms to the taxonomy.*

centralized mechanisms is illustrated in Fig. 2a. Each 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. 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 [9] 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 internetwork 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 internetwork coordination channels are still available. A coexistence scenario that employs coordinated mechanisms is illustrated in Fig. 2b. The coexisting networks coordinate with each other through various information signaling and retrieving techniques.

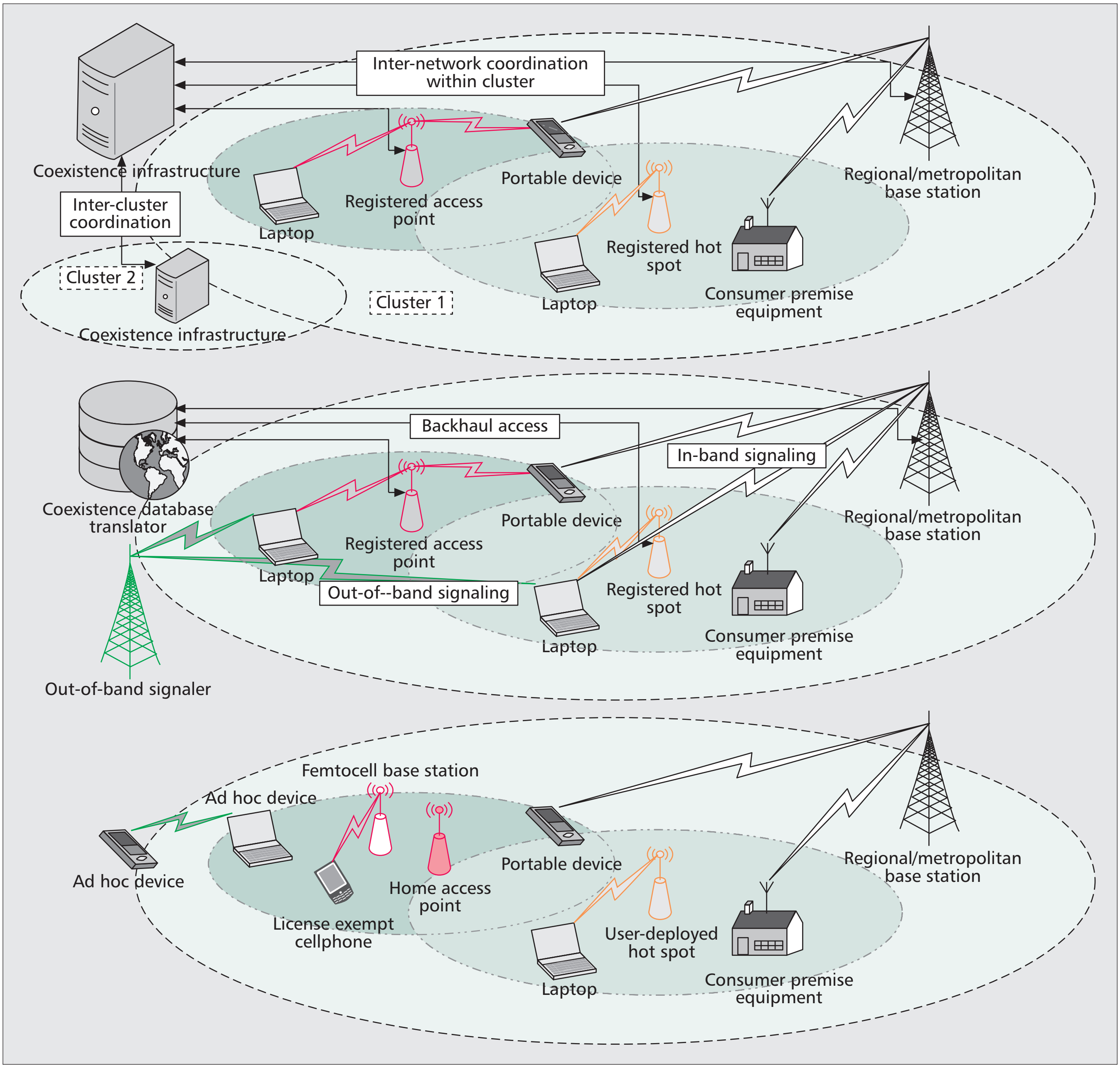

Figure 2. *Examples of heterogeneous coexistence scenarios: top, centralized mechanisms; middle, coordinated mechanisms; bottom, autonomous mechanisms.*

Based on the collected coexistence information, each network can make decisions to mitigate internetwork interference. For example, the *cooperative busy tone signaling* technique [13] 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 internetwork 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 internetwork 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. 2c. Each coexisting network performs resource allocation and manages internetwork 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 internetwork interference due to their best-effort nature.

Classification by Coexistence Mechanism's Control Channel

The availability of control channels for internetwork coordination directly determines the design of HC mechanisms. Based on the coexistence mechanism's control channel (CMC), HC 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 require internetwork 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. 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 HC mechanism when coexisting networks can decode signaling messages between them. The *collocated coexistence messaging* technique [10] 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. 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* [1] 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 internetwork 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. 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* [2], which is implemented on servers connected to the Internet, provides on-demand lookup functionality. The *Internet server-facilitated messaging* technique [2] enables internetwork 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 under which autonomous mechanisms (CMA-3) are classified.

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

Classification by Coexistence Cycle State

The simplified cognition cycle of a CR consists of three states: observation, decision, and adaptation [17]. Based on this cycle, we propose a classification of HC 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 internetwork 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 internetwork 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 [11] enables each IEEE 802.15.4 network to scan multiple channels potentially interfered with by IEEE 802.11 networks, and keep searching for a better channel selection by using the 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 internetwork 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.

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-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, learning-based *opportunistic channel access* techniques [11, 12] 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 occupied by primary users. Interference prognostication mechanisms offer low-power networks more opportunities for 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 internetwork 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 one is available, or wait until the channel becomes vacant. If coordination channels are available, internetwork 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 [15] 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 internetwork interference is tolerable. However, their effectiveness is usually limited, especially when interference comes from high-power interferers that belong to different operators.

Classification by Placement in the Protocol Stack

In general, internetwork interference is mitigated in the MAC or PHY layer of the protocol stack. Based on the placement in the protocol stack (PPS), HC 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 ways: each 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 accessing 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 subsequent timeframes. 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 internetwork 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 internetwork 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 internetwork interference. For example, *smart antennas* can be used to reduce 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.

Classification by Coexistence Mechanism's Synchronicity

The mitigation of internetwork interference can be facilitated by coexistence mechanisms synchronized across coexisting networks. Based on the coexistence mechanisms synchronicity (CMS), HC mechanisms are classified into *synchronized* and *unsynchronized* categories.

CMS-1: Synchronized Mechanisms — A number of coexistence techniques require accurate internetwork synchronization at either the MAC or 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, internetwork synchronization is difficult to implement without extra infrastructures to support.

CMS-2: Unsynchronized Mechanisms — Internetwork 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 carrier sense multiple access (CSMA) for IEEE 802.15.4 networks, and does not require synchronization with co-channel IEEE 802.11 networks using CSMA as well. Unsynchronized mechanisms can be readily implemented. However, in most cases, they can only alleviate internetwork interference but cannot avoid it.

Classification by Coexistence Mechanism's Memory Usage

Certain HC mechanisms require the storage of coexistence information. Based on the coexistence mechanism's memory usage (CMM), HC 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 amount of memory. For example, the *collocated coexistence messaging* technique for each multiradio user terminal directly forwards signaling messages from one of its home networks to another one without the need to record 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 resources. However, their achieved performance in terms of fairness, spectrum utilization, or throughput may not be as good as that of memory-required mechanisms due to limited coexistence knowledge.

Conclusion

In this article, we propose a comprehensive taxonomy of HC mechanisms used by networks operating in TVWSs. We describe the distinguishing features of the mechanisms in each cat-

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

Memory-free mechanisms are suitable for autonomous networks that do not have much system resource. However, their achieved performance may not be as good as that by memory-required mechanisms due to limited coexistence knowledge.

egory, and also discuss the relevant implementation issues. Furthermore, we provide a table that maps the existing HC mechanisms to the categories defined in the proposed taxonomy. Through this taxonomy, our aim is to offer a clear picture of the HC issues and related technical challenges, and shed light on the possible solution space.

Acknowledgement

This work was supported in part by the National Science Foundation under grants CNS-0746925, CNS-0831865, CNS-0910531, and CNS-1054697, and the Institute for Critical Technology and Applied Science at Virginia Tech.

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