

Survey of Spectrum Sharing for Inter-Technology Coexistence

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Abstract—Increasing capacity demands in emerging wireless technologies are expected to be met by network densification and spectrum bands open to multiple technologies. These will, in turn, increase the level of interference and also result in more complex inter-technology interactions, which will need to be managed through spectrum sharing mechanisms. Consequently, novel spectrum sharing mechanisms should be designed to allow spectrum access for multiple technologies, while efficiently utilizing the spectrum resources overall. Importantly, it is not trivial to design efficient spectrum sharing mechanisms, not only due to technical aspects, but also due to regulatory and business model constraints. In this survey we address spectrum sharing mechanisms for wireless inter-technology coexistence by means of a *technology circle* that incorporates in a unified, system-level view the technical and non-technical aspects. We thus systematically explore the spectrum sharing design space consisting of parameters at different layers. Using this framework, we present a literature review on inter-technology coexistence with a focus on wireless technologies with the same spectrum access rights, i.e. (i) primary/primary, (ii) secondary/secondary, and (iii) technologies operating in a spectrum commons. Moreover, we reflect on our literature review to identify possible spectrum sharing design solutions and performance evaluation approaches useful for future coexistence cases. Finally, we discuss spectrum sharing design challenges and suggest potential future research directions.

Index Terms—spectrum sharing, inter-technology coexistence, wireless technologies.

I. INTRODUCTION

In order to cope with the growing wireless traffic volume demands, significant changes in wireless technology deployments are expected in the near future. Two important trends can be distinguished: (i) the already ubiquitous wireless networks are predicted to undergo extreme densification [1], and (ii) an increasing number of spectrum bands are being targeted by multiple wireless technologies, e.g. LTE was recently proposed to operate in the 5 GHz unlicensed band [2]–[4], the 3.5 GHz Citizens Broadband Radio Service (CBRS) band in the U.S. is under discussion for being open to more technologies [5]. These trends will, in turn, increase the level of interference and the complexity of wireless inter-technology interactions, which have to be managed through efficient spectrum sharing mechanisms.

Traditionally, wireless technologies have operated in either licensed, or unlicensed bands. Licensed bands are granted by spectrum regulators to single entities, e.g. cellular operators,

which then individually deploy and manage their networks in dedicated spectrum bands. Consequently, inter-technology coexistence has not been an issue in these bands. By contrast, in the unlicensed bands any technology and device has equal rights to access the spectrum, as long as basic regulatory restrictions are met, e.g. maximum transmit power. As such, mutual interference among different technologies is inherent to the unlicensed bands and has typically been managed by rather simple distributed spectrum sharing schemes, e.g. between Wi-Fi and Bluetooth.

Recently, due to the growing need for higher network capacity, several regulatory and technical changes have been introduced for wireless technologies. Firstly, spectrum regulators have opened an increasing number of bands to *multiple* technologies, and have authorised novel access right frameworks, other than pure exclusive use or equal rights, i.e. different variants of primary/secondary access. Some examples of bands where such frameworks exist are: TV white space (TVWS) [6], [7], the recently proposed 3.5 GHz Citizens Broadband Radio Service (CBRS) band in the U.S. [5], and the 2.3–2.4 GHz band in Europe, where recent coexistence trials under Licensed Shared Access (LSA) have been conducted [8].

New challenging coexistence cases are also expected in the unlicensed bands, where LTE has recently been proposed and standardized to operate in the unlicensed 5 GHz band [2]–[4], where it must coexist with Wi-Fi. As both LTE and Wi-Fi are broadband technologies designed to carry high traffic loads, this is different to prior inter-technology coexistence cases in unlicensed bands (*cf.* Wi-Fi/Bluetooth coexistence). Furthermore, a *second* technology, i.e. Narrowband Internet of Things (NB-IoT) [3], has been recently designed to coexist with LTE in the same licensed cellular bands where LTE used to operate exclusively.

As demonstrated by these examples, a significant number of *heterogeneous* wireless devices, in terms of technologies and traffic requirements, is expected to be deployed in shared spectrum bands. It follows that new inter-technology interactions are currently emerging, and they are too complex to be efficiently managed by traditional spectrum sharing mechanisms designed for either licensed cellular bands, or unlicensed bands with low to moderate traffic volumes. It is thus crucial to design novel inter-technology spectrum sharing mechanisms that: (i) allow multiple devices and technologies to access the spectrum; and (ii) facilitate an efficient overall use of the spectrum, while fulfilling the requirements of each device/technology.

Furthermore, the design of inter-technology spectrum sharing mechanisms does not only depend on purely technical

aspects, but also on regulatory constraints, business models, and social practices. For instance, the regulators impose limits on the spectrum access rights for different devices/networks and in some cases even on the spectrum sharing mechanisms, e.g. LBT being mandatory for the 5 GHz unlicensed band in Europe [9]. Business models and social practices affect the design of spectrum sharing mechanisms, as the most efficient mechanisms from a technical perspective may not be practically feasible due to e.g. lack of agreements among the involved network managers/device owners.

Two important questions arise, pertinent to designing future wireless technologies: **(i) how to design in a systematic manner efficient spectrum sharing mechanisms especially for inter-technology coexistence, by taking into account technical and non-technical parameters;** and **(ii) how to evaluate their coexistence performance, with respect to a given technology itself, and its impact on other coexisting technologies.**

In this survey we explore the first question by means of a multi-layer *technology circle* that incorporates in a system-level view all relevant technical and non-technical aspects of a wireless technology. The technology circle, as proposed in [10] and illustrated in Fig. 3, includes the seven layers of the OSI stack and introduces the regulatory framework at Layer 0, and business models and social practices at Layer 8. The technology circle thus represents a unified design space for spectrum sharing, consisting of parameters at different layers. Next, we identify the layers at which spectrum sharing is implemented, and the layers that impose constraints. We then discuss the individual effect of each layer on spectrum sharing and the feasibility of different design parameter combinations at different layers. To this end we present a classification of the literature on inter-technology coexistence, based on individual spectrum sharing design parameters at different layers. We focus mostly on coexistence under a regulatory framework with equal spectrum access rights and especially on a spectrum commons. Importantly, these are the most challenging coexistence cases, as the limitations imposed by regulators tend to be more relaxed, but multiple, diverse technologies may share the same band, such that the design of spectrum sharing mechanism must take into account interactions with a wide range of other technologies.

We address the second posed question by discussing the choice of performance evaluation methods and metrics in the literature on inter-technology coexistence. Finally, we reflect on the reviewed literature to determine suitable design approaches for future wireless technologies and we identify challenges and possible research directions.

Earlier surveys addressing inter-technology spectrum sharing [11]–[23] focused on only specific coexistence cases and did not present a comprehensive view of inter-technology wireless coexistence in general. These surveys considered either spectrum that is shared in a primary/secondary manner, i.e. through dynamic spectrum access (DSA) techniques [11]–[19], or coexistence solutions in the form of integrated, coordinated technologies, e.g. mobile cellular and vehicular communications [20], converged heterogeneous mobile networks [21], and interworking architectures for wireless tech-

nologies [22]. Some early literature on Wi-Fi/LTE coexistence in the unlicensed bands was surveyed in [23]. Therefore, existing literature lacks a general and comprehensive view of inter-technology interactions, which is especially important for the most challenging coexistence case, i.e. spectrum sharing when multiple technologies have the same rights to access the spectrum. **Our survey, instead, presents wireless inter-technology coexistence from a unified, system-level perspective**, which is essential for answering the two posed research questions. Moreover, we focus especially on coexistence in a spectrum commons, which we expect to be of high practical relevance in the near future.

The rest of this survey is structured as follows. In Section II we define the inter-technology coexistence problem in terms of interference and we present an interference taxonomy. In Section III we present the technology circle and we discuss the impact of different layers on spectrum sharing mechanisms. Section IV presents our literature review of inter-technology coexistence within a hierarchical regulatory framework with a focus on technologies with the same spectrum access rights, i.e. primary/primary and secondary/secondary. Section V presents our literature review of inter-technology coexistence in a spectrum commons. In Section VI we discuss the main findings of this survey and we identify challenges and potential future research directions. Section VII concludes the survey.

II. INTERFERENCE TAXONOMY & PROBLEM STATEMENT

In this section we present an interference taxonomy and we define our problem statement for wireless inter-technology coexistence in terms of interference types. We also present the spectrum management terminology used in this survey.

Interference consists of perturbing signals that arrive at a receiver at the same time as the signal of interest. Consequently, the signal-to-interference-and-noise ratio (SINR) is decreased at the victim receiver, such that decoding the useful signal becomes more difficult. Spectrum regulators consider interference when establishing operational bounds for devices, or technologies. From an engineering perspective, interference is important for determining the achievable data rates, depending on the capabilities of the radio hardware (e.g. filter characteristics, receiver noise figure). Increased interference thus decreases the link capacity, which in turn affects the overall network capacity. We note that although interference fundamentally occurs at the Physical (PHY) layer, interference mitigation techniques are also implemented at other layers, especially at the MAC. The final link capacity is thus affected by such techniques, as well.

Interference can be classified according to the imperfections of the transmitter and receiver, and the relative portions of the spectrum where the interfering transmitter and the victim receiver operate. There are a few terms widely used in this context, but their meaning is sometimes loosely defined, as summarized in Table I. We identify two types of terminology used to refer to interference, based on the scope: (i) **generic** terms typically used in the regulatory domain, which is concerned with interference from another frequency band

TABLE I
INTERFERENCE CLASSIFICATION AND TERMINOLOGY BASED ON THE RELATIVE SHIFT BETWEEN THE SPECTRUM PORTIONS WHERE THE INTERFERER TRANSMITTER AND VICTIM RECEIVER OPERATE

Spectrum used / Terminology scope	Same frequency for interferer Tx and victim Rx	Different frequencies for interferer Tx and victim Rx
Generic	<i>in-band interference</i> [24]	<ul style="list-style-type: none"> • <i>out-of-band emissions</i> [25] (also <i>out-of-band interference</i> [26]) – due to Tx • <i>spurious emissions</i> [25] (sometimes included in out-of-band interference [24]) – due to Tx • <i>adjacent band interference</i> [26] – due to Rx
Technology-oriented	<i>co-channel interference</i> [24], [26]	<ul style="list-style-type: none"> • <i>adjacent channel interference</i> [24], [27]: • <i>adjacent channel leakage</i> [27] – due to Tx • <i>adjacent channel selectivity</i> [27]/ <i>rejection</i> [28] – due to Rx

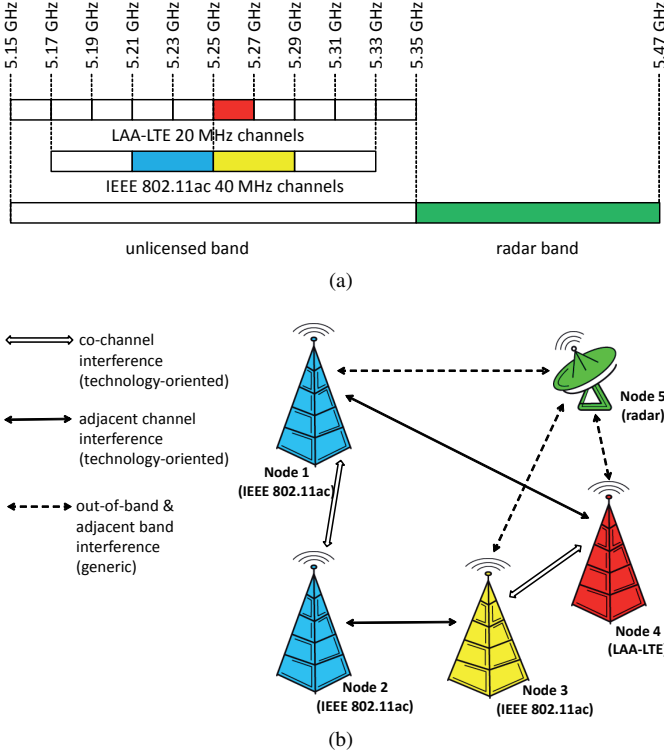


Fig. 1. Example of (a) two spectrum bands, where one is used as unlicensed by IEEE 802.11ac Wi-Fi [28] and LAA-LTE [3], and the other is allocated to radar services in Europe [29]; and (b) types of mutual interference occurring between different nodes operating in these bands: Nodes 1, 2, and 3 are IEEE 802.11ac Wi-Fi nodes operating on the 40 MHz channels in the same respective colour (blue and yellow), Node 4 is an LAA-LTE node operating on a 20 MHz channel (red), and Node 5 is a radar node operating on a channel in the radar band (green).

and limits imposed on the transmitters; and (ii) **technology-oriented** terms that refer mostly to interference among devices within given technologies with further channel partitioning of the same spectrum band, where each device is allowed to access any of these channels. Fig. 1 shows examples of different types of interference among IEEE 802.11ac Wi-Fi, Licensed Assisted Access (LAA) LTE, and radars operating in the 5 GHz band.

Interference from a **generic** perspective can be *in-band*, if both interfering transmitter and victim receiver operate in the same spectrum band [24]. In case the transmitter and receiver do not operate in the same band, the interference can be in the form of: *out-of-band emissions/interference*, *spurious*

emissions, or *adjacent band interference* [24]–[26]. Out-of-band and spurious emissions refer to interference caused by the imperfection in the filters of the transmitter. We note that spectrum regulators are typically concerned with these kinds of interference, since regulation traditionally imposes operational limits on the transmitters and not the receivers. Adjacent band interference was used in [26] to refer to the interference experienced by the receiver due to its own inability to perfectly filter out the received power in a band adjacent to the one it operates on.

From a **technology-oriented** perspective, where several channels are defined within a given band, the interference is defined with respect to the channel, not the band. We thus identify *co-channel interference* for operation over the same channel [24], [26] and *adjacent channel interference* (ACI) for operation on adjacent channels [24], [27]. We note that co- and adjacent channel interference can occur both among devices of the same technology, and among devices of different technologies (*cf.* Fig. 1). Furthermore, it is important to distinguish between ACI caused by the imperfections of the interferer transmitter and imperfections of the victim receiver – as shown in Fig. 2 – as the performance of a technology in terms of link-level data rates depends on both. For instance, 3GPP [27] distinguishes, in case of LTE, between *adjacent channel leakage* (at the transmitter) and *adjacent channel selectivity* (at the receiver). The IEEE 802.11 standard [28] defines a similar concept to the receiver selectivity, i.e. *adjacent channel rejection*, and specifies the transmitter spectrum mask as an equivalent of the allowed adjacent channel leakage.

Problem Statement

In the context of multiple wireless technologies operating in the same spectrum band, an important aspect is achieving *inter-technology coexistence*, which refers to the ability of two or more co-located technologies to carry out their communication tasks without significant negative impact on their performance. A consistent informal definition is reported in [30]. We note that the definition of coexistence that we adopt in this survey is rather general, in order to span the wide range of interpretations in the literature: some works use specific coexistence goals and metrics (e.g. achieving a minimum throughput value), whereas others study the coexistence impact on the performance of each technology in terms of various metrics (e.g. throughput, delay, packet collision probability, etc.), but do not target a specific coexistence goal.

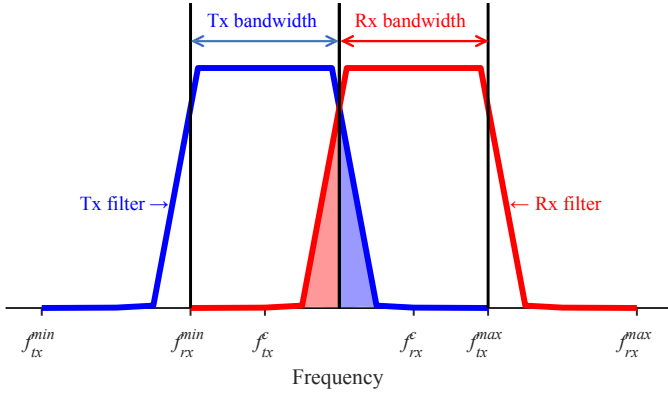


Fig. 2. Illustration of ACI as determined by the filters of the interferer transmitter (blue) and victim receiver (red). The ACI caused by the power leaked by the transmitter is shown as the area coloured in light blue. The ACI due to imperfect receiver filtering is shown as the area coloured in light red.

We discuss this further in our literature review in Section V (see especially Tables VII, IX, X, XI).

Wireless inter-technology coexistence can be achieved by mitigating *co- and adjacent channel interference*, as these types of interference occur when multiple devices of different technologies share the same spectrum band. In order to mitigate this inter-technology interference and allow access to the spectrum for multiple devices, spectrum sharing mechanisms are typically implemented at Layer 2, in a similar manner as for traditional MAC schemes mitigating intra-technology interference. Such solutions allow each device to use only a portion of the spectrum resources, e.g. in time or frequency, while experiencing lower levels of interference. It follows that each device will still experience a decrease in capacity when other portions of the spectrum resources are occupied by other devices. For example, a single device is allowed to transmit for a shorter time duration (e.g. time division multiple access – TDMA – in cellular networks, carrier sense multiple access with collision avoidance – CSMA/CA – in Wi-Fi), or over a portion of the frequency band (e.g. frequency division multiple access – FDMA – in cellular networks, channel selection in Wi-Fi). We discuss spectrum sharing mechanisms at Layer 2 further in Section III-B.

Spectrum Management Terminology

Spectrum management refers to the manner in which the spectrum is used in general, in order to facilitate wireless communication among different devices [31]. We identify the most important terms describing aspects of spectrum management as follows: spectrum rights, spectrum allocation, spectrum sharing.

Spectrum rights is typically used by spectrum regulators to describe who is entitled to use a certain portion of the spectrum and under which conditions. Spectrum rights are also relevant for engineers, who have to design and deploy technologies and devices that use the spectrum within the limits set by the spectrum regulators.

Spectrum allocation/assignment is used in a regulatory context, where the spectrum regulator grants a certain party the rights to use a particular portion of the spectrum [31]. A related term that is widely used, but does not have a regulatory connotation, is **channel allocation**, i.e. the channels on which different devices operate within a band, as configured by network managers.

Spectrum sharing is broadly defined by ECC “as common usage of the same spectrum resource by more than one user. Sharing can be performed with respect to all three domains: frequency, time and place.” [31] In this survey we adopt a similar definition as the one given by ECC, but we also include spectrum sharing via coding.

III. SPECTRUM SHARING: A SYSTEM-LEVEL VIEW

The design, implementation, and performance of spectrum sharing schemes is determined by a multitude of inter-related factors beyond the pure technical approach. As such, in order to maximize the spectrum utility for individual devices and/or networks, spectrum sharing should be analysed from a system-level perspective that takes into account the technical, regulatory, and business aspects of wireless technologies.

In [10] the technical and non-technical aspects of wireless technologies were identified and grouped into nine layers forming a *technology circle*, as shown in Fig. 3. Layers 1–7 are the technical layers of the OSI stack (i.e. Physical, Data Link, Network, Transport, Session, Presentation, Application¹), whereas Layers 0 and 8 model the regulatory, and business and social aspects, respectively. As the circular representation suggests, there is an inter-dependence between all these layers, which together form a large design parameter space that determines the candidate spectrum sharing mechanisms: some layers correspond to the actual implementation of these mechanisms, whereas other layers impose design constraints. Specifically, the major spectrum sharing mechanisms are implemented at Layer 2, and some at Layer 1, as summarized in Table II. Nonetheless, there are exceptions where sharing mechanisms are implemented at other layers, e.g. duplexing and DSA database at Layer 0. Most of the design constraints for spectrum sharing are specified at Layer 0, but also at Layers 7 and 8. We note that Layers 3 and 4 may have an indirect influence on the efficiency of inter-technology spectrum sharing mechanisms, by e.g. limiting the size of the packets transmitted through fragmentation, or varying the data rate of the traffic flow; however, this is outside the scope of this survey.

Importantly, not all combinations of technical and non-technical parameters at different layers are feasible when designing spectrum sharing mechanisms for inter-technology coexistence, and out of those that are feasible, some may be preferred over others. For instance, when deploying traditional cellular networks, each operator has exclusive rights to access the spectrum at Layer 0. This case is thus suitable for implementing spectrum sharing mechanisms at Layer 2 that are centrally coordinated, as a single operator manages the

¹In real implementations (e.g. TCP/IP stack), the functionality of Layers 5–6 is integrated in Layer 7; we thus discuss only the *Application* layer.

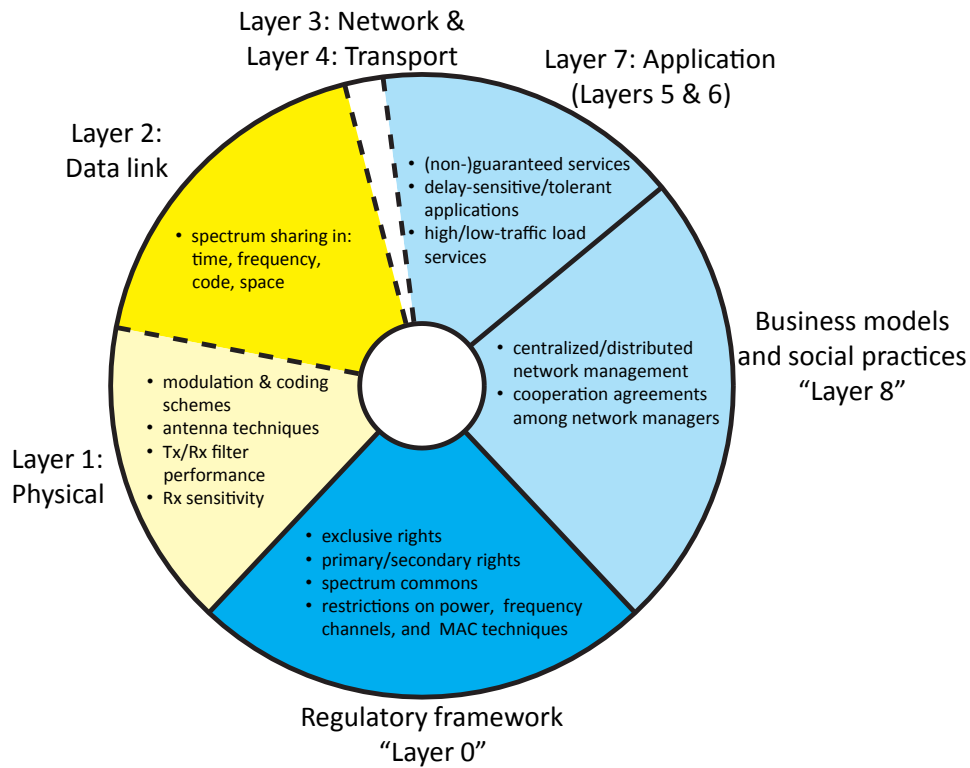


Fig. 3. Technology circle [10] as a system-level framework for considering the design space of inter-technology spectrum sharing. Most of the spectrum sharing mechanisms (yellow) are implemented at Layer 2 and a few at Layer 1. The main constraints (blue) on spectrum sharing design are found at Layer 0 and some at Layers 7 and 8. The main features of each layer are summarized in the figure.

TABLE II
SPECTRUM SHARING TAXONOMY BASED ON THE TECHNOLOGY CIRCLE

Scope		Spectrum sharing techniques		Layer	
Intra-technology	link level	in time: TDD		0	
		in frequency: FDD		0	
		full duplex		1	
	network level	in frequency: FDMA, OFDMA (and NC-OFDMA), channel selection, frequency reuse		2	
		in time	periodic transmissions: TDMA, (adaptive) duty cycle	2	
			random access: without spectrum sensing, e.g. ALOHA, slotted ALOHA; LBT and no random backoff, e.g. ETSI frame based equipment (FBE); LBT with random backoff and fixed contention window (CW), e.g. ETSI load based equipment (LBE) B; LBT with random backoff and adaptive CW, e.g. CSMA/CA, ETSI LBE A		2
			in code: CDMA		2
		in space: SDMA		2	
		other: power control		2	
Inter-technology	in frequency: distributed channel selection, DSA techniques (database, spectrum sensing)		0, 2		
	in time: random access, distributed periodic, DSA techniques (database, spectrum sensing)		0, 2		
	in code: FHSS, DSSS		1		
	in space: geolocation & DSA techniques (database, spectrum sensing)		0, 2		
	other: power control – distributed, DSA techniques (database, spectrum sensing)		0, 2		

entire network at Layer 8. Consequently, cellular networks are ideally suited to carry delay-sensitive traffic such as voice (at Layer 7), as the performance of the centrally-managed network can be readily predicted and optimized. We note that, for this example, inter-technology coexistence only occurs for multiple integrated technologies (e.g. LTE and NB-IoT), which are deployed by the same operator (at Layer 8).

Let us now consider a spectrum band where different networks operate based on primary/secondary spectrum rights at Layer 0. The primary network can then implement coordinated

spectrum sharing mechanisms at Layer 2 as a result of typically having a single network manager at Layer 8 (i.e. similarly to cellular networks). The operation of the secondary networks is strictly limited at Layer 0 to ensure primary protection, e.g. by specifying a maximum allowable interference power from the secondary networks to the primary. As such, the access of the secondary networks to the spectrum can be coordinated at Layer 0 through a reliable database operated by a third party at Layer 8, e.g. for TVWS. By contrast, interactions among secondary devices can be managed by distributed spectrum

sharing mechanisms at Layer 2, as they do not have the right to any protection at Layer 0; it follows that it is not straightforward to guarantee the quality of the services offered by these secondary networks at Layer 7 [13], [32].

Lastly, in a spectrum commons like the unlicensed bands, where various technologies coexist and have the same spectrum access rights at Layer 0, distributed spectrum sharing mechanisms have been a popular choice at Layer 2. Fully centralized coordination is typically not feasible for this example, due to the lack of business agreements among numerous networks managers at Layer 8.

As illustrated by these examples, there is a tight inter-connection between the technical and non-technical design parameters and constraints at different layers. It is critical to consider these interconnections in a unified system-level view, as different parameter combinations result in specific inter-technology interactions. Correctly identifying and evaluating these interactions lays the foundation for a robust development framework for new wireless technologies that result in efficient spectrum use.

In this survey we adopt the technology circle proposed in [10] as a framework to facilitate our system-level analysis of inter-technology spectrum sharing. In the following we briefly describe each layer of the technology circle and we highlight its impact on the design of spectrum sharing mechanisms. We first discuss Layer 0, which specifies the main constraints on spectrum sharing, but which also includes a few sharing mechanisms; we then present Layer 2 where most of the spectrum sharing mechanisms are implemented; subsequently, further sharing mechanisms at Layer 1 are presented; lastly, we discuss further constraints at Layers 7 and 8.

A. Regulatory Framework Constraints & Spectrum Sharing at Layer 0

Layer 0 primarily defines regulatory constraints for spectrum sharing mechanisms at Layers 2 and 1. However, a few spectrum sharing mechanisms are actually implemented at this layer. In this section we first discuss the regulatory constraints and then spectrum sharing at Layer 0.

1) *Constraints at Layer 0*: The regulatory framework consists of the regulatory limitations imposed on the use of spectrum. These determine who is allowed to use the spectrum, for how long, and within which technical parameter constraints, e.g. transmit power. Consequently, spectrum sharing mechanisms have to be designed and optimized under these constraints.

As shown in Fig. 4, spectrum access rights span a continuum of access models, from exclusive use of spectrum, i.e. exclusive spectrum access rights for a single network or technology, to a spectrum commons, where all devices/networks/technologies have the same rights to access the spectrum. Spectrum access rights between these extremes include the primary/secondary spectrum use model, where secondary networks must give priority to the dominant primary network. We note that the vast regulatory literature on spectrum access rights is out of the scope of this survey and we instead refer the interested reader to [15], [33]–[35].

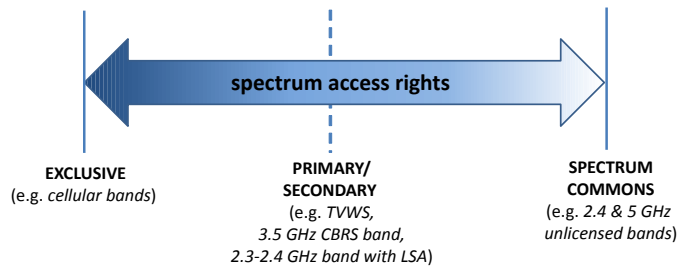


Fig. 4. Spectrum access rights based on the regulatory framework.

Traditionally, the spectrum access rights applied in practice have been at the two extremes in Fig. 4. On the one hand, exclusive rights to access the spectrum have been granted to e.g. mobile cellular networks, where each operator buys a license for a given spectrum band. Since there is a single operator deploying and managing the network, the regulators do not need to impose rules on the spectrum sharing techniques; the regulatory restrictions instead largely focus on transmit power levels and filter masks, in order to limit the interference towards other out-of-band networks/services.

On the other hand, in the unlicensed bands – an example of a spectrum commons – any device/technology/network has the same rights to access the spectrum (e.g. the 2.4 GHz and the 5 GHz unlicensed bands). Since such bands are open in principle to any technology, the spectrum regulators may decide to impose some restrictions also on the spectrum sharing mechanisms at Layer 2, such that multiple coexisting technologies have the opportunity to access the spectrum. For instance, in Europe ETSI requires devices to implement listen-before-talk (LBT) at the MAC layer, where each device must sense and detect the medium free from other transmissions before starting its own transmission [9]. Additionally, for the channels in the 5 GHz unlicensed bands where radar systems operate, mechanisms like dynamic frequency selection (DFS) and transmit power control (TPC) are specified in regulation [9], [36], [37], in order to protect radar operations.

Over the last fifteen years, several measurement studies have investigated how efficiently spectrum is used [38]–[42]. The main findings revealed that some of the allocated spectrum with exclusive rights is not used to its full capacity. Consequently, other models for spectrum access rights have emerged, with the general aim of allowing more dynamic access to the spectrum, based on demand. However, incumbent technologies operating in these bands still have priority when accessing the spectrum, such that hierarchical primary/secondary regulatory frameworks are needed.

Three recent examples where hierarchical regulatory frameworks are applicable are: TVWS, the CBRS band, and other bands granted through LSA, e.g. 2.3–2.4 GHz [8]. TVWS refers to the spectrum initially allocated for TV broadcasting, the coverage of which is not uniform, such that in particular locations the spectrum could be reused by other technologies with secondary access rights [6], [7], e.g. IEEE 802.11af Wi-Fi [28], LTE [43], IEEE 802.19.1 [44], or IEEE 802.22 [45]. We note that this spectrum access framework has only recently been adopted by a few regulators, i.e. FCC in the

U.S. and Ofcom in the U.K., and practical deployments are still in their infancy [46]. A three-layer hierarchical regulatory model is currently under discussion for the 3.5 GHz CBRS band in the U.S. [5] with: incumbent access, priority access, and general authorized access (GAA). The spectrum access system (SAS) manages the spectrum access of the secondary systems, corresponding to the two latter spectrum access layers. LSA is specified by the ECC in Europe [31] and is primarily intended for mobile broadband operators that are willing to share spectrum with existing incumbents. We note that other models for spectrum access rights have also been proposed in the literature [12], but have thus far largely not been adopted in practice.

Importantly, inter-technology coexistence can occur for any model of spectrum access rights. However, the most challenging coexistence cases are expected in the unlicensed bands as an example of a spectrum commons, where any technology is allowed to transmit while complying with rather relaxed rules. As such, there is also a growing tendency to extensively use unlicensed bands by different technologies. One example trend is to aggregate unlicensed spectrum, e.g. LTE in the licensed bands aggregates carriers in the unlicensed bands (as carrier Wi-Fi [47], LAA [2], [3], or LTE-U [4]); and Wi-Fi aggregates multiple channels in the 5 GHz unlicensed band [28]. Moreover, both future 5G cellular technologies [48] and IEEE 802.11ad Wi-Fi [28] aim at extending their operation to the unlicensed 60 GHz band.

2) *Spectrum Sharing at Layer 0*: In hierarchical regulatory frameworks, spectrum sharing between primary/secondary networks is implemented through DSA mechanisms. In such deployments where the primary users are protected from the secondary users, e.g. TVWS, the secondary users typically acquire knowledge on the availability of channels from a database operated by a third party [6], [7]. In fact, there is a strong inter-connection among spectrum sharing in **frequency**, **time**, **space**, and **power** in such networks, i.e. the DSA database is a central coordinator that gives information on the availability of the channels in certain locations and imposes limits on the transmit power and duration of use for the secondary networks. We consider these to be fundamental constraints imposed by the database on how the secondary networks access the spectrum and we include such spectrum sharing mechanisms at Layer 0. We note that primary/secondary spectrum sharing could also be implemented in a solely distributed manner using spectrum sensing, or spectrum sensing could be used as additional input for DSA databases, but we consider such techniques as belonging to Layer 2, similarly to other sensing-based spectrum access mechanisms, e.g. CSMA/CA. Notably, many DSA and supporting cognitive radio techniques have been proposed in the literature [13], [16]–[19], [32], but have not yet been implemented in commercial deployments.

Finally, duplexing can be considered a spectrum sharing mechanism between the two directions of a single link, that is implemented at Layer 0 through regulatory and technical restrictions on channelization. Here we can distinguish frequency division duplexing (FDD) and time division duplexing (TDD), as shown in Table II.

B. Spectrum Sharing at Layer 2

The majority of spectrum sharing mechanisms are implemented at Layer 2 of the technology circle. Although the focus of this survey is on inter-technology spectrum sharing, here we also present and discuss a taxonomy of intra-technology spectrum sharing, as the mechanisms implemented by devices within a technology can also affect the interactions with other technologies.

1) *Intra-Technology Spectrum Sharing*: From an intra-technology network-level perspective, multiple devices within the same network have to access the same spectrum. In this context spectrum sharing is performed by the MAC sub-layer of Layer 2. Spectrum sharing in such a case can be performed in: (i) **frequency**; (ii) **time**; (iii) **code**; or (iv) **space**.

Spectrum sharing in frequency: The traditional technique is frequency division multiple access (FDMA), which divides the allocated band into multiple sub-carriers, which are then allocated to different users, e.g. in GSM. A similar concept, but with a finer frequency division granularity is orthogonal frequency division multiple access (OFDMA), which divides the band into closely-spaced orthogonal sub-carriers, e.g. in LTE and WiMAX. Furthermore, frequency division can be used as a spectrum sharing mechanism between devices, without necessarily being implemented as a MAC protocol, e.g. channel selection/allocation for Wi-Fi, which can increase capacity and reduce interference among Wi-Fi devices [49]. Frequency reuse techniques have been applied analogously for cellular networks [50]–[53].

Spectrum sharing in time: This has traditionally been implemented among users in cellular networks through scheduled time division multiple access (TDMA), which is an instance of periodic transmissions that are centrally coordinated. A more general concept is duty cycling, which also refers to non-coordinated or only locally-coordinated periodic transmissions. Originally, duty cycling was proposed for sensor networks [54] with the aim of reducing energy consumption. Recently, it has also been adopted by broadband technologies such as LTE-U, which implements adaptive duty cycling [4]. A fundamentally different approach is random access in time, e.g. ALOHA and its variant slotted ALOHA. Also random, but implementing carrier sensing, are LBT mechanisms, e.g. CSMA/CA for Wi-Fi and several other LBT variants specified by ETSI [9].

Spectrum sharing via coding: For multi-user networks this is known as code division multiple access (CDMA) and it is based on spread spectrum techniques at Layer 1. CDMA is implemented by allocating a unique code for each user and allowing all users to transmit over the same wide bandwidth. This was implemented in 3G systems like UMTS and CDMA2000, based on direct sequence spread spectrum (DSSS) at Layer 1.

Spectrum sharing in space: This is based on antenna directivity at Layer 1. Deploying directional antennas facilitates e.g. sectorization in cellular networks, and thus interference reduction and more aggressive frequency reuse [55]. As such, sectorization in cellular networks is used for combined spectrum sharing in space and frequency. A more recent multiple access technique is space division multiple access

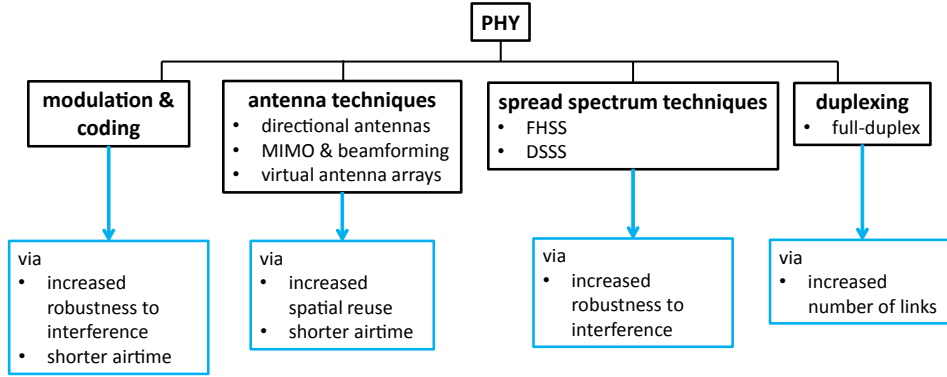


Fig. 5. Layer 1 techniques facilitating wireless inter-technology coexistence.

(SDMA) which emerged together with advanced antenna techniques at Layer 1. SDMA is based on using narrow beams pointed in the direction of the desired receiver, such that interference in other directions is reduced, which allows a higher number of simultaneous links over the same area, i.e. increases spatial reuse. We note that although the underlying Layer 1 techniques of sectorization and beamforming are similar, beamforming is a dynamic mechanism, whereas sectorization assumes a static antenna configuration. Multi-user multiple-input-multiple-output (MU-MIMO), i.e. an example of SDMA, has been standardized as an option in IEEE 802.11ac Wi-Fi [28], LTE [56], IEEE 802.16 WiMAX [57]. Example MU-MIMO MAC protocols for Wi-Fi were reviewed in [58].

Another method to share the spectrum, but not a MAC protocol, is transmit **power** control, which determines the transmission and interference range, and thus affects spatial reuse. Many technologies implement it as a mandatory or an optional feature, e.g. UMTS, LTE, Wi-Fi, sensor networks.

2) *Inter-Technology Spectrum Sharing*: For distributed spectrum access, the intra-technology spectrum sharing mechanisms can coincide with the inter-technology mechanisms at Layer 2, especially in the unlicensed bands, but also for secondary/secondary inter-technology coexistence in hierarchical regulatory models. Consequently, inter-technology spectrum sharing mechanisms can be implemented through (but are not restricted to) MAC protocols.

Inter-technology spectrum sharing can be performed in **frequency** through channel selection schemes. An example is LTE-U/LAA performing channel selection to avoid co-channel Wi-Fi devices [2]–[4]. Inter-technology spectrum sharing in **time** can be implemented in distributed networks at the MAC layer, through duty cycle transmissions (e.g. LTE-U) or through LBT MAC protocols (e.g. CSMA/CA for Wi-Fi and LBT for LAA). These mechanisms share the spectrum both within and among technologies. Another mechanism that facilitates both intra- and inter-technology coexistence for distributed networks is **power control**, which affects spatial reuse within and among technologies. This is considered for e.g. LAA [27], and the upcoming Wi-Fi amendment IEEE 802.11ax [59], [60].

Importantly, most current technologies implement more

than one spectrum sharing mechanism at Layer 2 to facilitate (both intra- and inter-technology) coexistence. Examples include GSM (FDMA and TDMA), LTE (OFDMA and TDMA), Wi-Fi (CSMA/CA, and optionally channel selection and SDMA), LTE in the unlicensed bands (duty cycle or LBT, and channel selection). We note that most technologies implement a variant of spectrum sharing in time and frequency, which suggests that these mechanisms are able to efficiently mitigate interference.

C. Spectrum Sharing and Interference Mitigation at Layer 1

The PHY layer can affect inter-technology coexistence through techniques that influence the design and performance of spectrum sharing mechanisms, as shown in Fig. 5. Furthermore, some of these techniques, i.e. spread spectrum techniques and full-duplex, can be seen as spectrum sharing mechanisms implemented directly at Layer 1, as summarized in Table II. We briefly discuss the PHY techniques in Fig. 5 in the following.

The PHY layer determines the manner in which the data is sent over the wireless channels, primarily through modulation and coding. Different combinations of modulation and coding schemes affect the spectrum reuse, since they may provide increased robustness to interference, so that the number of links that can be simultaneously active is increased.

Other mechanisms at Layer 1 that affect spectrum sharing are antenna techniques. Deploying directional antennas facilitates sectorization in cellular networks and beamforming based on multiple antennas supports SDMA mechanisms at Layer 2, as discussed in Section III-B. Also, using multiple-input-multiple-output (MIMO) antenna systems enables multiple data streams per link, which can increase the link capacity and reduce the effect of channel quality fluctuations through spatial diversity. Spatial diversity is also exploited through cooperative communication, which proposes virtual antenna arrays built with single-antenna devices. The impact of such techniques on the MAC in general is surveyed in [62].

Spread spectrum techniques have been used at Layer 1 to increase robustness against interference in intra- and inter-technology coexistence scenarios. Frequency hopping spread spectrum (FHSS) allows rather low data rates and is thus

TABLE III
CLASSIFICATION OF APPLICATIONS BASED ON USER REQUIREMENTS

Requirement	Classification	Examples
traffic volume	high traffic load (broadband)	file sharing, video steaming, and video conferencing through cellular broadband (e.g. LTE, 5G), and IEEE 802.11 Wi-Fi; some industrial applications for sensor networks with need for high sampling rate
	low traffic load	home and industrial applications for sensor networks (e.g. IEEE 802.15.4, ZigBee, NB-IoT, Bluetooth), M2M applications
delay	delay-tolerant	web browsing, file transfer, email, some sensor applications
	delay-sensitive	voice calls, streaming, some industrial IoT applications [61]
target end-user	human	web browsing, video conferencing
	machine	IoT, D2D, M2M

implemented by technologies like Bluetooth [63], which transports lower volumes of traffic. Direct sequence spread spectrum (DSSS) was used instead for technologies that transport moderate to high traffic volumes, e.g. IEEE 802.11b and code division multiple access (CDMA) systems like UMTS and CDMA2000.

Finally, recent interference cancellation techniques at Layer 1, which allow full-duplex communication, i.e. bidirectional for the same link at the same time, are a promising solution to increase spectrum utilization efficiency [64]. Full-duplex would impact spectrum sharing techniques at Layer 2, which would have to be redesigned (e.g. CSMA/CA for Wi-Fi [65]). We note that full-duplex can be considered a spectrum sharing technique at Layer 1, since it refers to sharing spectrum resources at the link level, by means of PHY techniques. By contrast, other duplexing techniques like FDD and TDD share the resources as determined by regulations at Layer 0.

D. Constraints of Applications at Layer 7

This layer can have a major impact on the design and performance of spectrum sharing mechanisms, since the specific requirements for each target application in a given network should be reflected in the choice of spectrum sharing technique. The applications can be grouped in different categories, according to their requirements in terms of traffic volume, delay, and target end-users, as shown in Table III. The application type affects the selected environment where the networks are deployed, their mobility patterns, and thus the interference characteristics. Coexistence in these specific conditions has to be managed by the spectrum sharing mechanisms.

E. Constraints of Business Models and Social Practices at Layer 8

Business models and social practices affect the network deployment likelihood, topology, ownership, and level of coordination. These result in different interference conditions. A taxonomy of business models is outside the scope of this survey, but we provide some examples to illustrate such interactions between technical and non-technical requirements.

Outdoor public cellular networks are owned and managed by mobile operators, as they have the financial resources to acquire a license for the cellular bands. Consequently, the spectrum sharing techniques can be centrally coordinated. However, outdoor base station (BS) deployments in private locations, e.g. on top of buildings, are restricted by the existence

of an agreement with the building owners. The optimization of the spectrum sharing parameters depends, in turn, on the physical locations of BSs and resulting propagation conditions.

By contrast, in private deployments, e.g. indoor residential Wi-Fi, there are multiple distributed networks, which operate individually, often with the default configuration. In Wi-Fi business deployments, a higher level of coordination is expected than in private deployments, e.g. for channel allocation or client-access point (AP) association, as there is a single manager configuring the network. A similar example are hotspot deployments. However, it may also occur that multiple hotspots from different operators transmit over the same spectrum, such that coordination can be achieved within a network managed by a single operator, but not among networks.

Finally, based on Layer 8 considerations we identify inter-technology interactions of two types: (i) integration and (ii) competition. Inter-technology *integration* refers to different technologies that interconnect, in order to increase capacity, or extend the range of the offered services, e.g. carrier Wi-Fi (i.e. integration of Wi-Fi into the 3GPP cellular networks for data offloading purposes [66], [67]); standardization of LAA LTE operating in the 5 GHz unlicensed band for capacity increase; and NB-IoT in LTE Advanced Pro (i.e. Release 13) for supporting device-to-device (D2D) IoT applications. Inter-technology *competition* occurs among different technologies that share the same spectrum, but for their individual offered services, e.g. secondary technologies operating within hierarchical regulatory frameworks; IEEE 802.15.4, Bluetooth, and Wi-Fi sharing the 2.4 GHz unlicensed band; LTE-U, LAA, and Wi-Fi sharing the 5 GHz unlicensed band. Importantly, interactions of the competition type lead to the most challenging inter-technology coexistence cases, where optimizing the overall spectrum utility is not trivial, due to the potentially greedy or conflicting individual goals for each technology.

F. Literature Review Structure

In the following sections we present a review of the literature addressing inter-technology coexistence and we classify the work according to different layers of the technology circle, as shown in Fig. 6. We first differentiate the work based on the regulatory framework at Layer 0, i.e. hierarchical in Section IV, and flat in Section V. For the hierarchical regulatory framework, we distinguish coexistence between *primary/primary*, *secondary/secondary*, and *primary/secondary* technologies. For coexistence within a flat regulatory frame-

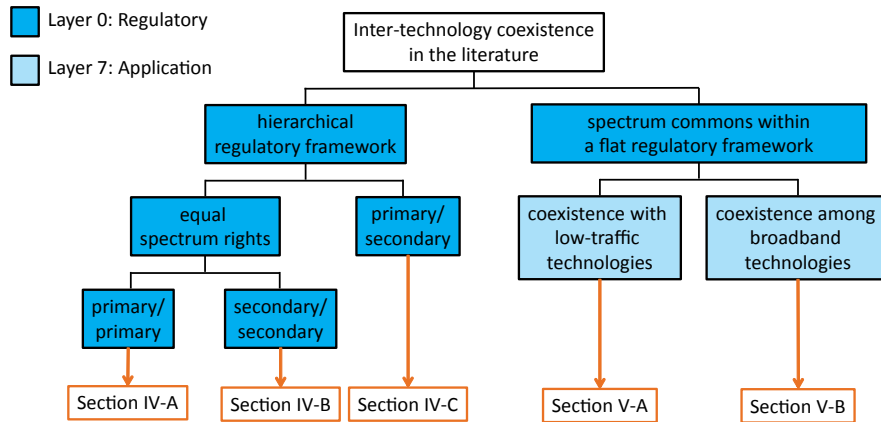


Fig. 6. Classification of research work in our literature review.

work, where all technologies have the same rights (i.e. *spectrum commons*), we classify the work further based on the Application Layer 7, i.e. *low-traffic* and *broadband* technologies. For each of the identified categories we review the spectrum sharing mechanisms at Layers 2 and 1.

IV. LITERATURE REVIEW OF INTER-TECHNOLOGY SPECTRUM SHARING WITHIN A HIERARCHICAL REGULATORY FRAMEWORK

This section focuses on inter-technology coexistence within a hierarchical regulatory framework. We first review existing work on inter-technology coexistence with equal spectrum rights, i.e. primary/primary in Section IV-A and secondary/secondary in Section IV-B. Then we give some examples of work on primary/secondary coexistence in Section IV-C. We note that primary/secondary inter-technology coexistence has already been extensively addressed in previous surveys [11]–[19] and so we give only a few representative examples from the recent literature.

A. Primary/Primary Coexistence

This section reviews the literature on primary/primary inter-technology coexistence, as summarized in Table IV.

Literature Overview: Primary/primary inter-technology coexistence occurs when different technologies are integrated, such that exclusive spectrum access rights at Layer 0 are assigned to a single entity that deploys and manages at Layer 8 a multi-technology network in the same spectrum band, e.g. cellular networks that incorporate LTE and NB-IoT. As such, designing inter-technology spectrum sharing mechanisms is less challenging and only a few papers addressed this by considering centralized mechanisms specific to cellular networks, i.e. channel allocation, power control, resource blanking.

The authors in [68] identified interference problems occurring when LTE coexists with an in-band NB-IoT deployment (i.e. both technologies use the same subcarriers) of the same operator, for the case where only some of the BSs are NB-IoT-capable. NB-IoT devices could thus associate to only some BSs, such that they may suffer from strong interference from BSs that are only LTE-capable. As coexistence solutions,

the authors investigated power boosting, i.e. the possibility to increase the downlink power for the NB-IoT resource blocks compared to that for LTE resource blocks; and resource blanking, i.e. not scheduling LTE transmissions on resource blocks that are used for NB-IoT by neighbouring BSs. The simulation results in [68] showed that LTE resource blanking was an efficient method to avoid co-channel interference for NB-IoT users. The authors suggested further coexistence solutions like narrowband transmission, coverage extension using repetition, and deploying NB-IoT in guard-band mode, i.e. transmitting on subcarriers not used by LTE.

By contrast, the authors in [69] considered LTE/NB-IoT coexistence, where the two technologies transmitted on different frequency channels. The effects of ACI were evaluated for different filter capabilities of the transmitter (i.e. ACLR) and of the receiver (i.e. ACS). The authors found through simulations that the effect of ACI on the LTE and NB-IoT networks was in general negligible.

B. Secondary/Secondary Coexistence

This section reviews the literature on secondary/secondary inter-technology coexistence, as summarized in Table IV. We review the work on: (i) the newly-available CBRS band in the U.S. in Section IV-B1; and (ii) TVWS in Section IV-B2.

Literature Overview: Only a few works have addressed secondary/secondary inter-technology coexistence in the CBRS band and they considered centralized channel allocation through a database. However, they only presented preliminary results and the addressed allocation issue is similar in any other centrally managed network. Most of the work focusing on secondary/secondary inter-technology coexistence in TVWS assumed that protection of the primary technology had been met, such that the addressed coexistence issues are in fact equivalent to those in a spectrum commons. We thus emphasize that secondary/secondary inter-technology coexistence mechanisms in the literature are similar to either those used for primary/primary or spectrum commons coexistence.

1) **CBRS band:** As discussed in Section III-A, spectrum access in the CBRS band is managed through SASs, where there is a three-layer hierarchical regulatory framework for access rights. An example of coexisting secondary technologies

TABLE IV
LITERATURE REVIEW OF INTER-TECHNOLOGY SPECTRUM SHARING WITH EQUAL RIGHTS, WITHIN A HIERARCHICAL REGULATORY FRAMEWORK

Spectrum Rights at Layer 0	Technologies	Ref.	Coexistence at Layer 2	Coexistence at Layer 1	Coordination at Layer 2 based on constraints at Layer 8
primary/primary	LTE/NB-IoT	[68]	LTE : resource blanking in time and frequency; NB-IoT : power boosting	–	centralized
		[69]	both technologies : adjacent frequencies	–	–
secondary/secondary	GAA users/GAA users in the CBRS band	[70], [71]	both technologies : channel allocation through SAS	–	centralized
		[72]	802.11af : likely CSMA/CA	–	–
	[73]	802.11af : CSMA/CA; 802.22 : busy tone	802.11af : signal pattern comparison	distributed	
	[74], [75]	Wi-Fi : CSMA/CA [74]; LTE : none	–	distributed	
	[76]	Wi-Fi : CSMA/CA; LTE : fixed duty cycle (0–80%) with different subframe blanking patterns	–	distributed	
	[77]	Wi-Fi : CSMA/CA; LTE : fixed and adaptive duty cycle, LBT, channel selection	–	distributed	

is coexistence among GAA users of different technologies, which was addressed in [70], [71]. The authors in [70] proposed schemes for fair allocation of the channels among GAA users managed by a SAS, i.e. static and max-min fair allocations. Since channel allocation is centrally performed by the SAS, we emphasize that this allocation problem is similar in any other centralized networks, e.g. cellular networks. The authors in [71] also proposed a scheme for the SAS to allocate channels dynamically to coexisting GAA devices, but this required the devices to perform carrier sensing and was based on graph theory and the transmission activity of each device. Examples of such users included Wi-Fi, LTE-U, LAA. We note that both [70], [71] are short poster papers that provide at most preliminary results.

2) *TVWS*: The authors in [72], [73] addressed coexistence between IEEE 802.11af and IEEE 802.22 in TVWS. We note that IEEE 802.11af accesses the spectrum based on CSMA/CA, whereas IEEE 802.22 implements scheduled transmissions. In [72] an evaluation of co-channel interference from IEEE 802.11af to 802.22 was presented, where no additional inter-technology coexistence mechanism was implemented, and it was found via OPNET simulations that the IEEE 802.22 upstream throughput was severely degraded. No results were presented for IEEE 802.11af. Also, it is not clear to which extent CSMA/CA for 802.11af was implemented in [72]. The authors in [73] proposed implementing a busy tone by the IEEE 802.22 nodes, in order to avoid 802.11af hidden nodes. Additionally, IEEE 802.11af compared the signal pattern of the busy tone and the 802.22 signal, in order to detect 802.22 exposed terminals. The proposed scheme was shown via simulations to provide an increase in the aggregate throughput over the case without busy tone, especially for high traffic loads.

A number of papers addressed Wi-Fi/LTE coexistence in TVWS [74]–[77]. Importantly, these papers did not consider the incumbent TV transmissions, so the addressed coexistence problem and the proposed solutions are the same as for Wi-Fi/LTE coexistence in the 5 GHz unlicensed band, which has been extensively studied in the literature and is

reviewed in Section V-B and summarized in Table VIII. In [74] an evaluation of the impact of Wi-Fi/LTE coexistence in TVWS was presented, where LTE did not implement any inter-technology coexistence mechanism. The authors found via simulations that Wi-Fi was severely affected, due to its CSMA/CA mechanism through which Wi-Fi deferred to LTE, whereas LTE transmitted almost continuously. By contrast, [75] evaluated the mutual interference between Wi-Fi/LTE at the PHY layer only (i.e. CSMA/CA was not modelled) and found via simulations that the performance of both technologies was degraded. The authors in [76] simulated blank subframe allocation for LTE to coexist with Wi-Fi in TVWS, with fixed duty cycle and different blank subframe patterns. Their main finding was that there was a tradeoff between Wi-Fi and LTE performance and that duty cycle tuning depended on deployment and requirements. The authors in [77] proposed fixed and adaptive duty cycle for LTE when coexisting with Wi-Fi and compared these schemes with LBT through simulations. Additionally, LTE could select less loaded channels. The authors found that LBT was more efficient than duty cycle for high traffic load, but claimed that LBT was not justified, given that LTE would likely avoid loaded channels. We note that the overall results reported for Wi-Fi/LTE coexistence in TVWS are consistent with those for Wi-Fi/LTE coexistence in the 5 GHz unlicensed band in Section V-B.

C. Primary/Secondary Coexistence

This section presents only some representative examples from the recent literature on primary/secondary inter-technology coexistence, as primary/secondary coexistence is not the focus of this survey and has already been extensively surveyed in [11]–[19]. Table V summarizes the considered examples, which show that an increasing number of bands are opening for multiple technologies. This can potentially lead to an increasing number of coexistence cases among technologies with the same spectrum access rights, i.e. secondary/secondary, or even to opening more bands as a spectrum commons in the future.

TABLE V
EXAMPLES FROM THE LITERATURE ON INTER-TECHNOLOGY COEXISTENCE WITH PRIMARY/SECONDARY SPECTRUM ACCESS RIGHTS

Technologies	Ref.	Coexistence for Secondary Technology at Layer 0	Coexistence for Secondary Technology at Layer 2	Coordination based on constraints at Layer 8
shipborne radars/CBRS devices	[78], [79]	in frequency and space based on SAS database and additional sensing network	–	centralized
(non-)governmental incumbents/LTE	[8]	time, frequency, and space based on an LSA system	–	centralized
radar/LTE	[80]	channels restricted for indoor use	LBT, TPC, DFS	distributed
radar/IoT	[81]	frequency, time, and space based on REM and SA database	–	centralized
IEEE 802.11p DSRC (ITS)/Wi-Fi	[82]	–	standardized CSMA/CA	distributed
	[83]	–	real-time channelization	distributed
	[84]	–	LBT with lower priority; reduced Wi-Fi transmit power	distributed
TV/LTE	[85], [86]	frequency, time, space through database	–	centralized
TV/IEEE 802.11af	[85], [87]	frequency, time, space through database	–	centralized
TV/next-generation cognitive radio TV (ATSC 3.0)	[88]	time, frequency, space based on database	spectrum sensing	centralized

Literature Overview: The reviewed works addressed coexistence in the CBRS band, radar bands, the band allocated to Dedicated Short-Range Communications (DSRC), and TVWS. Most of the spectrum sharing mechanisms were based on central coordination, due to the constraints at Layers 0 and 8. We note that for most of the primary/secondary coexistence cases, spectrum sharing is implemented at Layer 0 through a database that imposes fundamental restrictions on the way that the secondary technologies access the spectrum. However, for some coexistence cases, e.g. DSRC/Wi-Fi, distributed mechanisms were implemented at Layer 2. We note, however, that opening the DSRC band for Wi-Fi is still under discussion [89], so it has not yet been clarified through regulation which level of protection must be offered to DSRC.

The authors in [78] considered via simulations the case of incumbent shipborne radars coexisting with secondary CBRS devices, for which an additional sensing network had to detect the incumbents and report their presence to the SAS. Several algorithms were proposed for determining the sensing capabilities of these sensors and their placement. The work in [79] addressed a similar coexistence case and experimentally evaluated the evacuation time and the reconfiguration performance in the CBRS band for an SAS, where the incumbents were shipborne radars and the secondary users implemented LTE.

The first large-scale LSA implementation was presented in [8], where an LTE deployment coexisted with several incumbents in the 2.3–2.4 GHz band (e.g. fixed services, Programme-Making and Special Events – PMSE – video links). Several drive tests and simulations were conducted for functional and regulatory compliance verification.

The authors in [80] reviewed the spectrum sharing techniques imposed by regulators for LTE (but also valid for any other technology) to coexist with radars in the 5 GHz band. We note, however, that this is a short paper that did not present any performance evaluation results. The work in [81] proposed coexistence of IoT and rotating radars through an SAS with radio environmental maps, which shared the spectrum in frequency, time, and space. Results from a measurement campaign on

spectrum usage by rotating radars was presented, in order to show the coexistence potential with IoT.

The authors in [82]–[84] addressed coexistence between DSRC (or Intelligent Transportation Systems – ITS) devices and Wi-Fi in the 5.9 GHz band, which is currently under consideration for becoming open to Wi-Fi operations. In [82] potential DSRC/Wi-Fi coexistence issues were discussed, if Wi-Fi implemented its original CSMA/CA coexistence mechanism. The authors in [83] proposed a real-time channelization algorithm for IEEE 802.11ac Wi-Fi to coexist with DSRC devices, where the Wi-Fi APs selected a primary channel and bandwidth, such that the Wi-Fi throughput was maximized. Both experimental and simulation results were presented, showing that the Wi-Fi throughput was increased via the proposed scheme compared to static channel allocation. In [84] the performance of two mechanisms proposed in Europe for Wi-Fi to coexist with ITS was evaluated via simulations. Both mechanisms were based on LBT, as follows: the first mechanism used higher-duration sensing parameters when detecting ITS; the second mechanism probed for hidden ITS stations, and was able to vacate the channel. The authors found that there were three ITS transmitter-receiver distance ranges, corresponding to different coexistence characteristics: for short distances there were no coexistence problems; for medium distances outdoor Wi-Fi coexisted better than indoor Wi-Fi; and for long distances the ITS packet loss was high, but this was not considered problematic for safety applications.

The work in [85]–[88] addressed coexistence with primary TV services, where spectrum resources were shared through a centralized database, in frequency, time, and space domains. The authors in [85]–[87] experimentally verified the correct operation and performance of IEEE 802.11af and/or LTE in TVWS, through Ofcom’s TVWS trial pilot program. In [88] a different topic was addressed, i.e. an implementation of a next-generation cognitive radio TV based on the ATSC 3.0 standard, coexisting with legacy TV devices. We note that [88] is a short poster paper that did not present performance evaluation results.

TABLE VI
LITERATURE REVIEW OF INTER-TECHNOLOGY SPECTRUM SHARING WITH LOW-TRAFFIC TECHNOLOGIES IN A SPECTRUM COMMONS

Technologies	Ref.	Coexistence at Layer 2	Coexistence at Layer 1	Coordination at Layer 2 based on constraints at Layer 8
Wi-Fi/ IEEE 802.15.4	[90]– [93]	Wi-Fi: CSMA/CA; 802.15.4: CSMA/CA	–	distributed
	[94]	both: frequency selection	–	implicitly distributed
	[95]	Wi-Fi: CSMA/CA; 802.15.4: CSMA/CA, polling	–	distributed
	[96]	Wi-Fi: CSMA/CA; 802.15.4: adaptive channel allocation	–	local coordination for 802.15.4
	[97], [98]	both: CSMA/CA, relative shift in channel center frequency	Wi-Fi: beamforming [98]	distributed
	[99]	Wi-Fi: CSMA/CA; 802.15.4: CSMA/CA, adaptive power control	–	distributed
Wi-Fi/Bluetooth	[93], [100]– [102]	Wi-Fi: CSMA/CA	Bluetooth: FHSS	distributed
	[103]	Wi-Fi: CSMA/CA; both: MAC traffic scheduling	Bluetooth: FHSS	collaborative or non-collaborative
	[104], [105]	Wi-Fi: CSMA/CA; Bluetooth: scheduling	Bluetooth: adaptive FHSS	Bluetooth local coordination
	[106]	–	Wi-Fi: coded OFDM; Bluetooth: FHSS	distributed
	[107]	–	Wi-Fi: weighing sub-carriers; Bluetooth: FHSS, antenna diversity	distributed
	[108]	–	Wi-Fi: interference cancellation against Bluetooth	distributed
IEEE 802.15.4/ Bluetooth	[92]	802.15.4: CSMA/CA	Bluetooth: FHSS	distributed
IEEE 802.15.4/ microwave oven	[92]	802.15.4: CSMA/CA	–	distributed
Bluetooth/ {WCAM, RFID, microwave oven}	[100]	–	Bluetooth: FHSS	distributed
Wi-Fi/LTE D2D	[109]	LTE D2D: LBT, interference avoidance routing, switch to licensed band	–	distributed
5G/IEEE 802.15.4	[110]	–	5G: non-contiguous-OFDM, re-configurable antennas	distributed
LTE/ZigBee	[111]	LTE: two 0.5 ms guard periods per frame; 802.15.4: CSMA/CA	–	distributed
IEEE 802.15.4/ any interfering signal	[112]	–	802.15.4: collision detection at transmitter with full duplex (self-interference cancellation)	distributed

V. LITERATURE REVIEW OF INTER-TECHNOLOGY COEXISTENCE IN A SPECTRUM COMMONS

This section presents a review of the literature addressing inter-technology coexistence in a spectrum commons. We focus on the unlicensed bands as an example of a spectrum commons where the most diverse interactions between technologies occur, due to the largely technology-agnostic regulatory framework that allows any technology to operate in these bands without license costs, provided that the technical regulatory constraints at Layer 0 are met. We classify the abundant literature on this topic according to the Application-layer criteria in Table III, i.e. work that addresses: (i) coexistence with low traffic technologies in Section V-A, Tables VI-VII; and (ii) coexistence among high traffic technologies in Section V-B, Tables VIII-XI.

A. Coexistence with Low Traffic Technologies

The work reviewed in this section addressed: (i) IEEE 802.11 Wi-Fi/IEEE 802.15.4 in Section V-A1;

(ii) IEEE 802.11 Wi-Fi/Bluetooth in Section V-A2; and (iii) other technologies in Section V-A3. Table VI summarizes the spectrum sharing mechanisms and Table VII summarizes coexistence performance evaluation aspects, where *standalone* is sometimes considered as a baseline case where there is no other coexisting technology present.

Literature Overview: A similar number of works considered spectrum sharing mechanisms at Layer 2 and at Layer 1, for coexistence with low traffic technologies in a spectrum commons (*cf.* Table VI). This shows the importance of Layer 1 techniques in mitigating interference, especially for coexistence cases where at least one technology carries a low traffic volume. Furthermore, most of the work assumed distributed spectrum sharing mechanisms at Layer 2 as influenced by ownership at Layer 8, as expected in a spectrum commons. In terms of coexistence goals (see Table VII), most of the works compared the coexistence performance with either the standalone case, or coexistence without additional spectrum sharing mechanisms. We note that such an approach does not facilitate the performance comparison of different mechanisms

TABLE VII
INTER-TECHNOLOGY COEXISTENCE GOALS AND PERFORMANCE FOR LITERATURE REVIEW OF SPECTRUM SHARING WITH LOW-TRAFFIC TECHNOLOGIES
IN A SPECTRUM COMMONS IN TABLE VI

Technologies	Coexistence Goals	Performance Evaluation		
		method	metric	network size
Wi-Fi/ IEEE 802.15.4 [90]–[99]	<i>Impact on Wi-Fi</i> –(implicitly) vs. standalone [90], [93]–[95], [97] <hr/> <i>Impact on IEEE 802.15.4</i> –(implicitly) vs. standalone [91]–[93], [95]–[99] <hr/> <i>Other</i> –Wi-Fi packet error rate below 8% [94] –solve performance degradation of 802.15.4 [96]	–measurements [90], [92], [93], [95]–[99] –analytical [91], [94] –simulations [91], [96]	–throughput [90], [91], [93] –packet error rate/loss [90], [92], [94], [95], [97], [99] –packet delivery ratio/success rate [96], [98], [99] –received power [98] –channel power [95] –SIR [95] –delay [96]	– 1 link of each technology [90]–[93], [96]–[99] – 1 Wi-Fi link & several 802.15.4 devices [94], [95] – 100 802.15.4 devices and abstract interference [96]
Wi-Fi/Bluetooth [93], [100]–[108]	<i>Impact on Wi-Fi</i> –vs. standalone [93], [100]–[102], [106], [107] –vs. coexistence without additional spectrum sharing mechanisms [103], [105], [108] <hr/> <i>Impact on Bluetooth</i> –vs. standalone [93], [100]–[102], [107] –vs. coexistence without additional spectrum sharing mechanisms [103]–[105] –vs. other coexistence mechanisms in the literature [104], [105]	–measurements [93], [100], [101] –analytical [106] –simulations [101]–[105], [107], [108]	–throughput [93], [100], [101] –packet error rate/loss [100], [102], [104], [105], [107], [108] –delay [103]–[105] –jitter [105] –goodput [103], [105] –channel efficiency [104] –bit error probability [106]	– 1 link of each technology [93], [100], [101], [106]–[108] – 1 Bluetooth link & up to 2 Wi-Fi links [104], [105] – up to 10 Wi-Fi devices and several Bluetooth links [102], [103]
IEEE 802.15.4/ Bluetooth [92]	study mutual impact on both technologies (implicitly vs. standalone)	measurements	packet loss	two Bluetooth links and one 802.15.4 link
IEEE 802.15.4/ microwave oven [92]	study impact on 802.15.4 (implicitly vs. standalone)	measurements	packet loss	one 802.15.4 link and one microwave oven
Bluetooth/ {WCAM, RFID, microwave oven} [100]	study impact on Bluetooth vs. standalone	measurements	data rate, packet error rate	one Bluetooth link and one interferer of another technology
Wi-Fi/LTE D2D [109]	increase D2D throughput vs. different licensed/unlicensed spectrum use strategies	simulations	throughput	one Wi-Fi link and one multi-hop D2D flow
5G/IEEE 802.15.4 [110]	mitigate mutual interference vs. standalone & vs. coexistence with 5G without spectrum sharing mechanisms	simulations	throughput	one ZigBee and one 5G link
LTE/ZigBee [111]	study mutual impact between LTE and ZigBee vs. standalone	simulations	throughput, SINR	18 LTE BSs and 54 ZigBee APs
IEEE 802.15.4/any interfering signal [112]	detect collisions while transmitting	measurements	detection and false alarm probabilities	one 802.15.4 link and one 802.15.4 interferer

among themselves, so that selecting an efficient mechanism for future coexistence cases is not straightforward. The preferred performance evaluation methods were measurements and simulations. We emphasize that conducting measurements was facilitated by the existence of commercially available hardware (for e.g. Bluetooth, Wi-Fi, and IEEE 802.15.4), especially for works that did not propose new coexistence mechanisms. However, most of the work based on measurements considered very simplistic deployments of one link for each technology.

1) **IEEE 802.11 Wi-Fi/IEEE 802.15.4:** Coexistence between these technologies was addressed in [90]–[99]. The authors in [90]–[93] addressed coexistence for basic standardized

specifications, whereas [94]–[99] evaluated or proposed more advanced features to mitigate interference.

Specifically, the authors in [90] measured the impact of IEEE 802.15.4 on IEEE 802.11b performance. They found that the Wi-Fi throughput significantly decreased, due to the different sensing slots that the two technologies implemented. Unlike [90], the work in [91] addressed coexistence between these technologies from the point of view of IEEE 802.15.4 performance. The authors identified three coexistence ranges that characterized how the nodes of the two technologies can sense each other. The impact of coexistence with Wi-Fi on IEEE 802.15.4 was also evaluated in [92], which reported that

there was a strong impact on the IEEE 802.15.4 packet error rate, especially for high Wi-Fi load.

The authors in [94] evaluated the impact of IEEE 802.15.4 on 802.11b with frequency management via an analytical model and reported that Wi-Fi was only marginally affected, due to the considered frequency selection mechanism. The work in [95] reported similar results as in [92], i.e. that IEEE 802.15.4 suffered more performance degradation than 802.11b due to coexistence. Two solutions were further suggested to counteract this: reducing the Wi-Fi duty cycle (i.e. the duration of a frame vs. total time between two frames), or increasing the time duration of the IEEE 802.15.4 polling window. In [93], the mutual impact of coexistence between IEEE 802.11g and 802.15.4 was evaluated and compared to coexistence between IEEE 802.11g and Bluetooth. Consistent with the results reported in previous work, the performance of 802.15.4 was significantly affected by Wi-Fi. Also, it was reported that the Wi-Fi performance was affected by Bluetooth more than by IEEE 802.15.4. Although this effect was not explained in [93], it was likely caused by Bluetooth frequency hopping.

In [96] an adaptive channel allocation scheme was proposed for multi-hop IEEE 802.15.4 networks, in order to protect them from interference from IEEE 802.11b. The scheme required local coordination among IEEE 802.15.4 nodes, which temporarily formed a group and changed their channel if a high level of interference was detected. This scheme was found to be effective for improving IEEE 802.15.4 coexistence performance especially in large-scale networks.

The authors in [97] investigated via measurements the mutual effect of interference between IEEE 802.15.4 and 802.11b/g, where the channel center frequencies of the two technologies were gradually shifted with respect to each other. It was found that the packet error rate of 802.15.4 severely increased for frequency shifts lower than 7 MHz, but 802.11b/g was only marginally affected by coexistence; this was likely due to the much higher transmit power of 802.11 vs. 802.15.4. An experimental evaluation was also presented in [98], but focused only on the coexistence impact of IEEE 802.11g/n on 802.15.4 networks. Advanced network configurations were considered for Wi-Fi, i.e. beamforming and overlapping or non-overlapping channels. It was reported that the IEEE 802.15.4 network severely suffered in case of high Wi-Fi traffic load and that interference from adjacent channels may be critical. Also, the extent to which Wi-Fi beamforming decreased the IEEE 802.15.4 packet delivery ratio differed greatly depending on the beam orientations.

Unlike previous work, [99] focused on the impact of IEEE 802.11b Wi-Fi on 802.15.4 body area networks and found that the 802.15.4 packet loss was significantly affected only for the very low power regime. Adaptive power control was suggested as a solution.

2) **IEEE 802.11 Wi-Fi/Bluetooth:** Coexistence between these technologies was addressed in [93], [100]–[108]. The authors in [93], [100]–[102] assumed standard specifications, whereas in [103]–[108] advanced features were proposed.

The authors in [100] measured the impact of mutual interference between IEEE 802.11b and Bluetooth. They found

that the decrease in data rate was in general tolerable for both technologies. In [101] it was found through simulations and measurements that Bluetooth was less affected by Wi-Fi than vice-versa. This showed that the FHSS technique implemented by Bluetooth is quite effective when the hopping channels cover a wider band than a Wi-Fi channel. Also, the CSMA/CA MAC was not as efficient at mitigating interference that occurred with a high hopping rate. Regarding Wi-Fi/Bluetooth coexistence, [102] reported that: increasing the Wi-Fi transmit power did not reduce the Wi-Fi packet loss, so lower transmit power was found to be desirable; and a slower Bluetooth hopping rate caused less interference to Wi-Fi, consistent with results reported in [101].

The authors in [103] proposed two MAC traffic scheduling algorithms to cope with the interference between DSSS-based IEEE 802.11 and Bluetooth: the first algorithm scheduled and adjusted the Wi-Fi packets when coexisting with Bluetooth voice links, whereas the second one adjusted Bluetooth packets for data links when coexisting with Wi-Fi. Both algorithms could be applied in a collaborative or non-collaborative manner. The simulation results showed a significant increase in goodput for both technologies.

In [104] an adaptive frequency hopping mechanism was proposed for Bluetooth, which avoided channels used by DSSS Wi-Fi (i.e. IEEE 802.11b). The proposed scheme was compared with a scheduling scheme that backed off the Bluetooth transmission until the medium became idle, where both schemes used local coordination within the Bluetooth master-slave network. The proposed adaptive scheme was found to be more suitable for environments where the interference conditions did not change fast, such that the same hopping sequence could be used for longer, whereas the scheduling scheme was found to be more suitable for the opposite case. Similar findings were reported in [105].

The work in [106] evaluated the impact of Bluetooth interference on an OFDM-based system, i.e. IEEE 802.11g, through an analytical model. It was reported that the bit error probability of the OFDM system was strongly affected without any coding, but that coding efficiently mitigated interference from Bluetooth.

The impact of mutual interference between IEEE 802.11g and Bluetooth was investigated in [107] and interference mitigation methods were suggested. It was found that the mutual interference had a strong impact on both technologies in terms of packet error rate. Also, the performance could be improved through antenna diversity for Bluetooth, and through weighing of bits according to the interference level of the respective subcarriers for IEEE 802.11g.

The authors in [108] proposed a PHY-layer technique for IEEE 802.11g to reduce the impact of interference from Bluetooth. The proposed technique was based on interference cancellation by estimating the multipath channel and interference characteristics.

3) **Other Technologies:** Coexistence between other technologies where at least one of them is low-traffic was addressed in [92], [100], [109]–[112].

The authors in [92] evaluated the performance of IEEE 802.15.4 when coexisting with Bluetooth or microwave

ovens and reported that IEEE 802.15.4 was only marginally affected in terms of packet loss. The work in [100] reported measurement results for Bluetooth coexisting with a wireless camera (WCAM), RFID, and a microwave oven and showed that the data rate of Bluetooth could be significantly reduced, especially for short distances between Bluetooth devices and coexisting devices of a different technology.

The routing performance of LTE-based multi-hop D2D communications coexisting with Wi-Fi in the unlicensed band was investigated in [109]. Three coexistence mechanisms were considered for D2D: LBT with sensing until the channel is available; interference avoidance routing (i.e. routing around Wi-Fi, so as to avoid contention); and switching to the licensed cellular band. The authors found that LTE-based D2D in the unlicensed band could increase the LTE network-wide capacity, but suggested that efficient algorithms to select the D2D transmission time are needed, as they may impact Wi-Fi negatively.

The authors in [110] proposed Layer 1 techniques, i.e. non-contiguous-OFDM and reconfigurable antennas, for 5G to coexist with IEEE 802.15.4. However, this is a short paper where only preliminary results were presented. The coexistence performance of LTE and ZigBee (i.e. IEEE 802.15.4 at MAC and PHY layers) was evaluated in [111], for the 2.4 GHz band. Furthermore, two guard periods were proposed in each LTE frame, so that ZigBee could access the channel. The authors found that ZigBee's performance was degraded more than that of LTE, but that the requirements for smart meter communications with ZigBee were still met.

In [112] a collision detection mechanism for IEEE 802.15.4 transmitters was considered at Layer 1, in order to stop transmission in case of collision and thus save energy. The proposed mechanism was based on self-interference cancellation with an in-band full duplex radio, which could also detect collisions with any other signals.

B. Coexistence among Broadband Technologies

We first review the literature addressing coexistence among technologies of the IEEE 802.x standards in Section V-B1. We then focus on IEEE 802.11 Wi-Fi/LTE coexistence in the unlicensed bands, which has been recently extensively investigated in light of the two main proposed LTE variants for the unlicensed bands, i.e. LAA [27] and LTE-U [4]. We classify the existing literature based on the main Layer 2 coexistence approaches for LTE²: (i) no MAC coexistence mechanism, i.e. LTE continuously transmits, in Section V-B2; (ii) LBT, i.e. the approach adopted by 3GPP for LTE LAA [2], [3], in Section V-B3; and (iii) duty cycle, i.e. the approach adopted by the LTE-U Forum, in Section V-B4. Table VIII summarizes the spectrum sharing mechanisms in the reviewed literature and Tables IX-XI summarize coexistence performance evaluation

²We note that Wi-Fi always implements CSMA/CA at the MAC layer, i.e. LBT with binary exponential random backoff. Although different approximations were adopted for modelling CSMA/CA in different papers (e.g. [129] does not consider the MAC inefficiency due to sensing time, [134], [138], [139] assume random backoff with fixed CW, and [135] estimates the binary exponential random backoff by means of an analytical model), a detailed review of such modelling techniques is out of the scope of this survey.

aspects, where *standalone* refers to the baseline case with a single technology, i.e. no coexisting technology is considered, and *plain coexistence* refers to Wi-Fi/LTE coexistence where no spectrum sharing mechanism is implemented for LTE. Furthermore, in Tables IX-XI we group similar metrics in the literature under a few representative terms, e.g. *throughput* also refers to goodput [103], offered/served load [132], capacity [128], normalized throughput [133], etc.

Literature Overview: Only a few works have addressed coexistence among IEEE 802.x standards, as the dominant IEEE standard in the unlicensed bands is 802.11 Wi-Fi, such that the devices implement similar spectrum sharing mechanisms. There is a large number of works that have addressed Wi-Fi/LTE coexistence in the unlicensed bands. Some of them consider LTE without any coexistence mechanism and identify the need to implement one, in order to allow Wi-Fi to access the spectrum. Most works consider different variants of either LBT-LTE, or duty-cycle-LTE and compare them only with standalone technologies, or with coexistence where LTE does not implement sharing mechanisms. We note that this approach does not facilitate a direct comparison between different mechanisms. A few works, however, considered both Wi-Fi/LBT-LTE and Wi-Fi/duty-cycle-LTE coexistence. The authors report in general that the adaptive sharing mechanisms at Layer 2 (either duty cycle or LBT) achieve the best coexistence performance. However, some of these mechanisms require information that is not trivial to obtain with distributed mechanisms (e.g. traffic requirements, number of nodes, etc.). We note that many works have considered fairness when evaluating the coexistence performance, but different fairness definitions were used (*cf.* Tables X-XI). However, a significant number of papers have adopted the fairness criterion used by 3GPP, i.e. "not impact Wi-Fi services more than an additional Wi-Fi network" [27]. As such, some works found that the most fair coexistence performance was obtained when LTE implemented an LBT mechanism similar to Wi-Fi's LBT. Furthermore, there have been very few proposals for Layer 1 sharing mechanisms, which suggests that such techniques are not developed enough to mitigate interference for broadband technologies, such that the most efficient mechanisms are sharing in time and/or frequency at Layer 2. Finally, most of the works relied on simulations and analytical tools to evaluate the coexistence performance. Only few works have conducted basic experimental evaluations and only for duty-cycle-LTE. This shows the difficulty of obtaining such results due to the lack of devices that implement a fully functional open-source LTE stack, which could be modified in a straightforward manner for research purposes.

1) Coexistence among Broadband IEEE 802.x Technologies: The authors in [113], [114] addressed coexistence between legacy IEEE 802.11 devices implementing at the MAC the distributed coordination function (DCF) and new devices implementing enhanced distributed channel access (EDCA), i.e. different sensing durations, in order to grant different channel access priority levels for different traffic categories. The reported performance results validated the channel access priorities associated with different sensing durations [113]. Additionally, EDCA had higher channel access priority than

TABLE VIII
LITERATURE REVIEW OF INTER-TECHNOLOGY SPECTRUM SHARING AMONG BROADBAND TECHNOLOGIES IN A SPECTRUM COMMONS

Technologies	Ref.	Coexistence at Layer 2	Coexistence at Layer 1	Coordination at Layer 2 based on constraints at Layer 8
Wi-Fi EDCA/DCF	[113], [114]	both: CSMA/CA with different sensing time	–	distributed
Wi-Fi/ IEEE 802.16	[115]	Wi-Fi: CSMA/CA, transmit power; 802.16: transmit power	both: modulation	distributed
	[116]	Wi-Fi: CSMA/CA; 802.16: channel blocking, ordering contention slots	–	distributed
Wi-Fi/LTE	[117]–[139]	Wi-Fi: CSMA/CA; LTE: none	–	–
	[124], [129]	Wi-Fi: CSMA/CA; both: channel allocation (random [124], [129]; graph coloring [124]; avoid occupied channels [129])	–	distributed [124], [129]; coordinated [124]
	[140]	Wi-Fi: CSMA/CA; LTE: power control in the uplink	–	distributed
	[141]	Wi-Fi: modified CSMA/CA	both: decoding	colocated LTE and Wi-Fi receivers
	[142]	Wi-Fi: CSMA/CA	LTE: beamforming	distributed; LTE nodes also have 802.11 receivers
	[143], [144]	both: spectrum splitting between technologies (subcarrier granularity [144])	–	likely cooperative [143]; cooperative [144]
Wi-Fi/LBT-LTE	[129], [145]–[148]	Wi-Fi: CSMA/CA; LTE: <i>generic LBT</i> – different ED thresholds [146], ideal MAC and different channel selection schemes (random, least interfered) [129], based on ETSI LBE [147]	optimized topologies [148]	distributed [129], [145]–[147], likely centralized [148]
	[137], [149]–[151]	Wi-Fi: CSMA/CA; LTE: <i>LBT without random backoff</i> – [137] two time granularity levels; [149] ETSI FBE; additional adaptive transmission probability [150], adaptive transmission duration [151]; dynamic channel switch [151]	–	distributed [137], [149], centralized [151]
	[122], [123], [126], [134], [138], [139], [152]–[156]	Wi-Fi: CSMA/CA; LTE: <i>LBT with random backoff within fixed interval (or fixed CW)</i> – different ED thresholds [122], [134], [138], [139], [152], adaptive ED threshold [156], back-off freeze [152], variable transmission duration [153], [154], different channel selection schemes (random, least power at AP or UE) [139]	–	distributed
	[157]	Wi-Fi: CSMA/CA; LTE: <i>LBT w/o random backoff, and with random backoff and fixed CW</i>	–	–
	[121], [135], [158]–[164]	Wi-Fi: CSMA/CA; LTE: <i>LBT with binary exponential random backoff</i> – backoff freeze [160], different ED thresholds [160], different channel selection [135], [161]–[164], different transmit power [135], [161]	–	distributed
	[130], [165]	Wi-Fi: CSMA/CA; LTE: <i>LBT with random backoff with fixed CW and binary exponential</i> , based on ETSI load based equipment	–	distributed
	[166]–[169]	Wi-Fi: CSMA/CA; LTE: <i>LBT with random backoff and adaptive contention window (other than binary exponential)</i>	–	cooperative [166], distributed [167], cooperative among LTE [168], [169]
	–	–	–	–
Wi-Fi/ duty-cycle-LTE	[120], [127], [140], [159], [170]	Wi-Fi: CSMA/CA; LTE: <i>fixed duty cycle</i> – 80% with subframe granularity [140]; 0-100% with mean period 150 ms [120]; 0-80% with 100-1000 ms period duration [170]; 0-100% [127]; 50% with period 80 ms and maximum 20 ms ON time [159]	–	distributed
	[119], [123], [134], [171]	Wi-Fi: CSMA/CA; LTE: <i>fixed duty cycle with different subframe Tx patterns</i> – 50% [171]; 60% [119]; 50% successive/alternative and synchronous/asynchronous [123]; 33-67% fixed duty cycle with synchronous/asynchronous on/off pattern (not necc. subframe) [134]	–	distributed
	[125], [131], [136], [147], [149], [162], [163], [172]–[175]	Wi-Fi: CSMA/CA; LTE: <i>adaptive duty cycle</i> – channel selection [125], [162], [163], [172], [173]; carrier aggregation (channel width) [173]; power control [131], [175]	–	distributed [125], [136], [147], [149], [162], [163], [172]–[175], centralized [125], [131]
	[135], [161], [176]	Wi-Fi: CSMA/CA; LTE: <i>fixed and adaptive duty cycle</i> – fixed 20-100% [176], fixed 50% uncoordinated [161], fixed 50% coordinated/uncoordinated [135]; ideal TDMA (perfect scheduling) [135], [161]; different channel selection [135], [161]; different transmit power [161]	–	distributed [135], [161], [176], centralized [135], [161]

DCF, due to the different backoff counter decrement procedure, through which it gained one additional backoff slot [114].

Coexistence between IEEE 802.11a and 802.16 was addressed in [115], [116]. In [115] the mutual interference was

evaluated at the PHY layer, when transmissions from the two technologies overlapped in time and frequency. Furthermore, the authors suggested varying the transmit power and modulation scheme for coping with this interference. In [116] channel

TABLE IX
INTER-TECHNOLOGY COEXISTENCE GOALS AND PERFORMANCE FOR LITERATURE REVIEW OF SPECTRUM SHARING AMONG BROADBAND TECHNOLOGIES IN A SPECTRUM COMMONS IN TABLE VIII: Wi-Fi EDCA/DCF, Wi-Fi/IEEE 802.16, Wi-Fi/LTE

Technologies	Coexistence Goals	Performance Evaluation		
		method	metric	network size
Wi-Fi EDCA/DCF [113], [114]	study mutual impact between technologies vs. each other	–analytical [113], [114]; –OPNET simulations [113]	–throughput [113], [114]; –slot occupancy probability [114]	20–30 stations of each technology
Wi-Fi/IEEE 802.16 [115]	study mutual impact between technologies vs. each other	analytical, simulations	bit error rate	one Wi-Fi and one 802.16 link
Wi-Fi/LTE [117]–[144]	<p><i>Impact of coexistence with unmodified LTE on Wi-Fi</i></p> <p>–no baseline [117], [126], [136]; –vs. standalone [118]–[125], [127]–[129], [131]–[133], [137]; –vs. coexistence with itself [121], [130], [131], [134], [135], [138], [139]</p> <p><i>Impact of coexistence on unmodified LTE</i></p> <p>–no baseline [119], [126], [131], [134]–[136], [138]; –vs. standalone [122]–[125], [127]–[129], [132], [133], [137]; –vs. coexistence with itself [121], [139]</p> <p><i>Other</i></p> <p>–increase aggregate throughput vs. coexistence with unmodified LTE [124] –mutual coexistence impact vs. channel selection and vs. LBT [129] –mutual coexistence impact vs. standalone & vs. duty cycle [140] –enable simultaneous Wi-Fi and LTE transmissions and compare aggregate throughput with time division [141] –enable simultaneous LTE and Wi-Fi transmissions and compare with an LBT variant [142] –maximize total capacity, ensure fairness and QoS for both technologies [143] –maximize overall resource utilization vs. an LBT variant [144]</p>	<p>–simulations [121]–[125], [127]–[130], [133]–[141], [144];</p> <p>–analytical [117], [124], [126], [131], [132], [134], [138], [139], [143];</p> <p>–measurements [118]–[120], [131], [141]</p>	<p>–throughput [118]–[125], [127], [129]–[133], [135]–[137], [139]–[141], [143], [144]; –no. transmitted packets [118]; –channel/medium access probability [117], [126], [134]; –number/ probability of successful transmissions/links [126], [134], [138]; –delay [117], [125]; –jitter [119]; –SINR [124], [128], [131], [134], [141], [142]; –interference [134]; –coverage probability [134], [138]; –false sensing probability [141]; –mean square error [141]; –channel occupancy time [142]; –Jain’s fairness index [143]; –utility [144]</p>	<p>– 1 LTE link/eNB & several Wi-Fi devices [117]–[120], [131], [132], [136], [141], [142];</p> <p>– ≤10 APs of each technology [122], [123], [125]–[128], [130], [133], [135], [137], [140], [144];</p> <p>– ≤100 APs or 400–5000 APs/km² of each technology, or 50 total links [121], [124], [129], [134], [138], [139], [143];</p>

blocking and ordering of contention slots was proposed for IEEE 802.16, in order to reserve the channel before 802.11a and thus to guarantee QoS for 802.16. However, no performance evaluation results were presented.

2) **Wi-Fi/LTE Coexistence:** A number of papers investigated Wi-Fi/LTE coexistence performance when LTE does not implement any coexistence mechanism [117]–[139], either as an individual coexistence case, or as a baseline for comparison with other mechanisms. They all reported that the Wi-Fi performance was severely degraded and that LTE should implement an inter-technology coexistence mechanism when operating in the unlicensed bands.

For an overview of the main coexistence approaches considered for LTE in the unlicensed bands we refer the reader to [23], [133], [140], [149], [177]–[181], where [23] presented a survey of the early literature on Wi-Fi/LTE coexistence, and [180], [181] specifically focused on LAA standardized

by 3GPP.

The authors in [124], [140]–[144] proposed Wi-Fi/LTE coexistence solutions different than the MAC-based LBT and duty cycling. In [124] two variants of a channel allocation scheme based on multigraph coloring were proposed, i.e. with intra- or inter-technology coordination. It was found that inter-technology coordination did not improve the network throughput significantly compared to intra-technology coordination.

In [140] an uplink power control mechanism was proposed for LTE users, which resulted in a similar or higher user throughput for both LTE and Wi-Fi, compared to LTE with a duty cycle of 80%.

Two different PHY-layer techniques were proposed in [141], [142]. In [141] Wi-Fi and LTE could both transmit at the same time, on the same frequency, using a decoding method that enabled the separation of two overlapping OFDM signals. The authors in [142] proposed estimating the direction of arrival

TABLE X
INTER-TECHNOLOGY COEXISTENCE GOALS AND PERFORMANCE FOR LITERATURE REVIEW OF SPECTRUM SHARING AMONG BROADBAND TECHNOLOGIES IN A SPECTRUM COMMONS IN TABLE VIII: WI-FI/LBT-LTE

Technologies	Coexistence Goals	Performance Evaluation		
		method	metric	network size
Wi-Fi/ LBT-LTE [121]– [123], [126], [129], [130], [134], [135], [137]–[139], [145]–[169]	<p><i>Impact on Wi-Fi</i></p> <ul style="list-style-type: none"> –no baseline [153]; –vs. coexistence with itself [121], [130], [134], [135], [138], [139], [146], [149], [152], [155]–[167] –vs. plain coexistence [121]–[123], [126], [129], [134], [135], [137]–[139], [146], [149], [154], [161] –vs. standalone [122], [123], [137], [149], [162], [163], [165] –vs. channel selection [129], [135], [151], [161]–[163] –vs. duty cycle variants [123], [134], [135], [149], [151], [159], [161]–[163] –vs. other LBT variants [122], [123], [130], [139], [154]–[158], [160], [164]–[169] <hr/> <p><i>Impact on LTE</i></p> <ul style="list-style-type: none"> –no baseline [145], [153] –vs. plain coexistence [121]–[123], [126], [129], [134], [135], [137]–[139], [146], [149], [154], [161] –vs. coexistence with itself [121], [139], [152], [156], [160], [164], [166], [168] –vs. standalone [122], [123], [137], [149], [163] –vs. channel selection [129], [135], [139], [151], [163] –vs. duty cycle variants [123], [134], [135], [149], [151], [159], [161], [163] –vs. other LBT variants [122], [123], [130], [139], [154], [156]–[158], [160], [164]–[169] <hr/> <p><i>Other</i></p> <ul style="list-style-type: none"> –fairness (implicitly) for Wi-Fi vs. coexistence with itself [130], [139], [155]–[157], [159], [161]–[163], [166] –proportional fair rate allocation for Wi-Fi and LTE [147] –fairness as same Wi-Fi/LTE probability of successful tx [154] –fairness as same Wi-Fi/LTE airtime [158] –proportional fair channel switch [164] –fairness as minimization of collision probability to Wi-Fi [167] –fairness as constant aggregate Wi-Fi throughput [168] –airtime fairness for Wi-Fi based on altruistic gains [169] –maximize proportional fairness throughput for both [150] –maximize aggregate LTE capacity in presence of Wi-Fi [148] –enable different levels of protection for Wi-Fi [153] –maximize total throughput given requirements of each technology [157] 	<p>–simulations [121]–[123], [129], [130], [134], [135], [137]–[139], [145], [147]–[153], [155], [156], [158]–[164], [166]–[169];</p> <p>–analytical [126], [134], [138], [139], [146], [148], [153]–[155], [157], [159], [165], [167]–[169]</p>	<p>–throughput [121]–[123], [129], [130], [135], [137], [139], [145]–[168];</p> <p>–delay [147], [154], [155], [159], [165], [166];</p> <p>–coverage probability [134], [138], [148];</p> <p>–successful transmissions [126], [134], [138], [154];</p> <p>–buffer occupancy [152];</p> <p>–users in outage [152];</p> <p>–protection level [153];</p> <p>–transmission duration [153]</p> <p>–error function [150]</p> <p>–channel access probability [126], [155]</p> <p>–collision probability [155], [167]</p> <p>–SINR [156]</p> <p>–airtime [158], [169]</p> <p>–Jain’s fairness [158], [162], [163], [169]</p> <p>–channel occupation [167]</p> <p>–utility [168]</p> <p>–Q-value [168]</p> <p>–entropy [169]</p> <p>–risk-informed interference assessment [162], [163]</p>	<p>– 1 LTE link/AP & several Wi-Fi devices [147], [150], [153], [155], [158], [167]</p> <p>– ≤10 APs, or 15 APs/km² of each technology [122], [123], [126], [130], [137], [146], [151], [152], [154], [157], [159], [160], [164], [165], [168], [169];</p> <p>– 10–90 APs, or 400–5000 APs/km² of each technology: [121], [129], [134], [135], [138], [139], [145], [148], [149], [156], [161]–[163], [166]</p>

of Wi-Fi signals by LTE and then applying null steering, such that LTE does not cause interfere in the direction of Wi-Fi. The techniques in [141], [142] resulted in high coexistence performance, but they both required co-located LTE and Wi-Fi receivers. Additionally, [141] also requires substantial changes to the CSMA/CA Wi-Fi mechanism.

Unlicensed spectrum splitting between Wi-Fi and LTE was proposed in [143], [144]. The authors in [143] aimed to maximize the total Wi-Fi and LTE femtocell capacity, while taking into account fairness and QoS constrains. This scheme was shown to improve the capacity of the LTE femtocells, compared to licensed spectrum splitting between femtocells and macrocells. We note that although this is not explicitly stated in [143], the proposed scheme requires cooperation between Wi-Fi and LTE, as Wi-Fi is allowed to access only a

portion of the spectrum. In [144] subcarrier granularity was assumed and cooperation between LTE and Wi-Fi through controllers was proposed, where the controllers implemented decision trees and repeated games, in order to maximize their resource utilization. The controllers did not share information about their networks, but negotiated spectrum sharing. The scheme was shown to improve the throughput for both technologies compared to other LBT variants.

3) *Wi-Fi/LBT-LTE coexistence*: The works [121]–[123], [126], [129], [130], [134], [135], [137]–[139], [145]–[162], [164]–[169] addressed Wi-Fi/LBT-LTE coexistence.

a) *Generic LBT*: The work in [129], [145]–[148] assumed LBT models at a level of abstraction for which the specifics of the backoff type are irrelevant, so we refer to this as *generic LBT*. In [145] it was found that LTE had

a high capacity when sharing the spectrum with Wi-Fi, but no baseline was specified. The authors in [146] found that proper selection of the sensing threshold was beneficial for coexistence. In [129] two variants of LBT-LTE were considered, i.e. defer to Wi-Fi only, and defer to Wi-Fi and LTE, and different channel selection schemes, i.e. random or least-interfered channel. It was reported that the large number of channels and building shielding at 5 GHz ensure harmonious coexistence. Also, channel selection was found to be more efficient than LBT at ensuring coexistence. In [148] a complementary solution to LBT was proposed, i.e. a framework that statistically optimizes the LTE network topology when coexisting with Wi-Fi in indoor scenarios, such that the aggregate LTE capacity is maximized and the required coverage achieved. However, this requires accurate models for radio propagation, service demand, load levels, and spatial distribution.

b) LBT without random backoff: The work in [137], [149]–[151] considered LBT-LTE without random backoff. The authors in [137] proposed two variants of LBT with fixed sensing duration and two different time granularities. For fine time granularity, i.e. *periodic* sensing, LTE senses for a few OFDM symbols in each subframe and decides whether to transmit in the rest of the subframe. For coarse granularity, i.e. *persistent* sensing, LTE senses for one subframe and decides whether to transmit in the next few frames. Both schemes were found to provide a satisfactory user throughput for both LTE and Wi-Fi. LBT with fixed sensing time and adaptive probability of transmission when the channel is idle was proposed in [150]. The probability of transmission was adjusted to achieve the maximum proportional fairness throughput for both Wi-Fi and LTE. The authors in [151] proposed an LBT algorithm, where LTE directly transmits once the medium becomes idle. Additionally, based on the LTE and Wi-Fi traffic load, LTE either dynamically switches the channel to allow Wi-Fi to transmit (for low traffic load), or adaptively reserves some blank subframes for Wi-Fi (high traffic load). However, the estimation of the traffic load is performed in a centralized manner in the LTE core network, which requires information from both LTE and Wi-Fi nodes.

c) LBT with random backoff within fixed interval: The work in [122], [123], [126], [134], [138], [139], [152]–[156] addressed Wi-Fi coexistence with LBT-LTE with random backoff within fixed interval (or fixed CW). The authors in [122], [138], [152] considered a random backoff within a fixed interval, and different sensing thresholds. It was shown that if the LTE sensing threshold or random backoff interval were configured properly, Wi-Fi could coexist with LTE at least as well as with itself. Also, due to the high penetration loss through walls, coexistence between indoor Wi-Fi and outdoor LTE could be easily ensured [122]. The work in [139] evaluated LBT with random backoff within a fixed interval (as a simplified model of CSMA/CA without exponential backoff) and with various sensing thresholds, where LTE only deferred to Wi-Fi, but not to itself. Also, different channel selection schemes, i.e. random and least power, were considered. A tradeoff between Wi-Fi and LTE performance was reported, based on the configured parameters. In [153], [154] LBT-LTE

variants with fixed CW and variable transmission duration were proposed. In [153] LBT-LTE could free the medium for different durations, so that Wi-Fi could transmit and thus different levels of protection were achieved for Wi-Fi. In [154] the transmit duration of LBT-LTE was reduced after each failed transmission and the scheme improved Wi-Fi performance compared to other LBT variants (i.e. with constant CW and adaptive CW), especially for three LBT-LTE nodes coexisting with Wi-Fi. The authors in [126] evaluated LBT with fixed CW in simplistic scenarios and found that Wi-Fi performance was improved compared to the case where it coexists with LTE without any coexistence mechanism. The authors in [155] evaluated coexistence for different fixed CW and found that Wi-Fi and the total system performance could be increased if the CW was properly selected. The authors in [156] proposed LBT with adaptive sensing threshold, where the threshold was adapted differently in case of Wi-Fi, LTE intra-operator, or LTE inter-operator interference. Thus, LTE capacity gains could be obtained compared to a fixed threshold, while harmoniously coexisting with Wi-Fi.

d) LBT without random backoff and with random backoff within fixed interval: The authors in [157] considered both LBT-LTE without random backoff, and with random backoff and fixed CW. They investigated which is the optimal CW size for maximizing the throughput of Wi-Fi and LTE, while satisfying the requirements of each. A comparison with LTE with deterministic backoff, i.e. fixed-duration channel sensing, was presented.

e) LBT with binary exponential random backoff: The authors in [121], [135], [158]–[162], [164] addressed Wi-Fi coexistence with LBT-LTE with binary exponential random backoff. The authors in [158] considered LTE with the standardized parameters in 3GPP Release 13 for LAA and proposed a distributed algorithm to adapt the transmission time, such that it matched that of Wi-Fi in case of saturated traffic. The work in [121] assumed LTE with a sensing threshold of -62 dBm, similarly to Wi-Fi, and it was found that the LTE throughput performance was better due to better spectral efficiency, but also that LBT-LTE could be more fair to Wi-Fi (implicitly vs. LTE without LBT coexisting with Wi-Fi) and could improve the overall performance of Wi-Fi and LTE with a suitable sensing threshold. The authors in [160] considered different sensing thresholds, and backoff freeze for LTE. They further proposed an LBT implementation similar to the one for IEEE 802.11ac, in order to vary the channel width by aggregating multiple unlicensed carriers. The main findings were that the LBT mechanism could be tuned to be more polite towards other networks, according to the scenario and load. In [164] a proportional fair dynamic channel selection mechanism was proposed for LBT-LTE in order to coexist with Wi-Fi. A modification to binary exponential LBT was also introduced, i.e. a frozen period to ensure correct channel switching decision. The scheme was shown to be efficient especially for low traffic load.

f) LBT with random backoff within fixed interval, or binary exponential: The authors in [130], [165] considered LTE with two versions of LBT, i.e. with random backoff with fixed CW and binary exponential, based on ETSI LBE. In [130]

it was found that LBT was not enough to ensure fairness with Wi-Fi and that fine tuning was needed. Specifically, it was suggested that LBT should match Wi-Fi's CSMA/CA design as closely as possible. Consistently, [165] found that a fixed CW was more beneficial for LTE, but at the same time degraded Wi-Fi performance more.

g) LBT with random backoff and other adaptive CW:

The authors in [166]–[169] considered LBT-LTE with random backoff and adaptive contention window (other than binary exponential). The authors in [166] proposed adapting the CW based on ETSI LBE, in order to guarantee channel access fairness and QoS fairness. The proposed mechanism achieved better performance than a fixed CW, but required cooperation between technologies, in order to exchange QoS metrics. The authors in [167] proposed adapting the CW based on the Wi-Fi traffic load and available bandwidth. Fairness for Wi-Fi was achieved in terms of collision probability and throughput, in combination with additional admission control for LTE. The authors in [168] proposed adaptive CW based on the cell load and the transmission probability of LTE and Wi-Fi. Two methods were considered in order to obtain the optimum CW that maximises LTE utility and maintains Wi-Fi throughput, i.e. a genetic algorithm and multi-agent reinforcement learning. It was shown that both schemes performed equally well, but the genetic algorithm was more time-consuming. In [169] the CW of LTE was adapted based on LTE cooperation and the Shapely value, in order to achieve airtime fairness among LTE and Wi-Fi. LTE implemented LBT based on ETSI LBE and also had to estimate the number of Wi-Fi nodes by sensing the medium. The authors found that their proposed scheme based on the Shapely value was more fair than the weighted proportional fairness, in terms of the entropy and Jain's fairness index for the airtime.

4) Wi-Fi/Duty-Cycle-LTE Coexistence: The following work in the literature considered Wi-Fi/duty-cycle-LTE coexistence [119], [120], [123], [125], [127], [131], [134]–[136], [140], [147], [149], [159], [161], [162], [170]–[176].

a) Fixed duty cycle: The authors in [120], [127], [140], [159], [170] considered LTE with fixed duty cycle. Some basic results were presented in [140], in order to show the performance of LTE subframe blanking, compared to no LTE coexistence mechanism and LTE uplink power control. The authors in [120] varied experimentally the fixed duty cycle, the transmit power, and the LTE bandwidth and center frequency. They found that the results are vendor-specific and fine tuning for fairness was difficult, so more experimental results were required. In [170] it was reported that duty-cycle-LTE was unfair to Wi-Fi and that other coexistence approaches should be considered. Similarly, [127] found that the Wi-Fi performance was impacted, but that this could be adjusted by restricting the LTE activity. However, it was concluded that more research was needed for sophisticated coexistence schemes.

b) Fixed duty cycle with different transmission patterns:

The authors in [119], [123], [134], [171] considered LTE with fixed duty cycle with different transmission patterns. The authors in [171] proposed two analytical models that estimated the probability of collision and throughput for Wi-Fi, while

also incorporating the capture effect. They validated their models against ns-3 simulations for LTE with a fixed duty cycle of 50% and different sub-frame transmission patterns. It was found that the Wi-Fi performance strongly depended on the packet size. Adjusting the duty cycle and duty cycle period was suggested, in order to improve Wi-Fi performance. The authors in [119] performed an empirical evaluation for a fixed duty cycle of 60% and different sub-frame transmission patterns. They found that coexistence was possible, but that tuning the network parameters was non-trivial, especially since muting patterns that resulted in higher Wi-Fi throughput also resulted in higher Wi-Fi jitter.

c) Adaptive duty cycle: The authors in [125], [131], [136], [147], [149], [162], [172]–[175] considered LTE with adaptive duty cycle. In [172] carrier sense with adaptive transmission (CSAT), which implements adaptive duty cycle and channel selection based on sensed interference, was evaluated. Additional puncturing (i.e. short off-time during the longer on-time) was introduced to protect Wi-Fi delay-sensitive applications. The authors found that LTE could coexist with Wi-Fi at least as well as Wi-Fi coexisting with itself. The authors in [173] optimized the network utility through a cognitive coexistence scheme that takes into account fairness for Wi-Fi and determines dynamically the channel selection, channel width (i.e. how many carriers to aggregate), and transmission time for LTE. Although the scheme is distributed, the server performing the optimization requires information about the Wi-Fi network, which was proposed to be obtained through packet sniffing. In [174], an adaptive duty cycle mechanism was proposed for LTE, in order to ensure fairness with Wi-Fi. LTE adapted the probability of accessing the channel and its transmission duration through proportional fair allocation, such that Wi-Fi and LTE could get equal fractions of time to transmit on the channel. Similarly, [136] aimed at achieving proportional fairness in terms of average airtime at link level. However, the LTE nodes had to be additionally equipped with Wi-Fi interfaces, in order to estimate the channel utilization. The authors in [131] proposed a framework for centralized coordination between LTE and Wi-Fi, through which the adaptive duty cycle mechanism and transmit power were optimized, such that a similar throughput was achieved for the two technologies. A multi-armed bandit machine learning mechanism was proposed in [175] to adapt the duty cycle. Additionally, transmit power control was implemented for the LTE downlink, in order to maximize the energy efficiency. The adaptive duty cycling was shown to achieve considerable gains in the aggregate Wi-Fi and LTE throughput over fixed duty cycling, and the power control improved the energy efficiency over the case without power control. We note however, that these findings are somewhat trivial, given the selected baselines. In [125] dynamic channel selection through sensing (called “adaptive LBT”), and adaptive duty cycle were proposed for LTE to coexist with Wi-Fi. However, no evaluation results were provided.

d) Fixed and adaptive duty cycle: The authors in [135], [161], [176] considered LTE with both fixed and adaptive duty cycle. Specifically, [176] proposed an adaptive duty cycle mechanism based on reinforcement learning, and compared its

TABLE XI
INTER-TECHNOLOGY COEXISTENCE GOALS AND PERFORMANCE FOR LITERATURE REVIEW OF SPECTRUM SHARING AMONG BROADBAND TECHNOLOGIES IN A SPECTRUM COMMONS IN TABLE VIII: WI-FI/DUTY-CYCLE-LTE

Technologies	Coexistence Goals	Performance Evaluation		
		method	metric	network size
Wi-Fi/ duty-cycle-LTE [119], [120], [123], [125], [127], [131], [134]–[136], [140], [147], [149], [159], [161]–[163], [170]–[176]	<p><i>Impact on Wi-Fi</i></p> <ul style="list-style-type: none"> –no baseline [174]; –vs. coexistence with itself [134], [135], [149], [149], [159], [161]–[163], [172], [173]; –vs. plain coexistence [119], [120], [123], [127], [131], [134]–[136], [140], [149], [161], [172], [176]; –vs. standalone [119], [120], [123], [127], [140], [149], [162], [163], [171], [175]; –vs. channel selection [135], [161]–[163], [173]; –vs. other duty cycle variants [119], [123], [127], [134], [135], [161], [170], [171], [175], [176]; –vs. LBT variants [123], [134], [135], [147], [149], [159], [161]–[163]; –vs. power control [131], [140] <hr/> <p><i>Impact on LTE</i></p> <ul style="list-style-type: none"> –no baseline [174]; –vs. plain coexistence [119], [120], [123], [127], [131], [134]–[136], [140], [149], [161], [172], [176]; –vs. coexistence with itself [172]; –vs. standalone [123], [127], [140], [149], [163], [175]; –vs. channel selection [135], [161], [163], [173]; –vs. other duty cycle variants [119], [123], [127], [134], [135], [161], [175], [176]; –vs. LBT variants [123], [134], [135], [147], [149], [159], [161], [163]; –vs. power control [131], [140] <hr/> <p><i>Other</i></p> <ul style="list-style-type: none"> –fairness as difference between Wi-Fi performance loss ratio (vs. standalone) and a function of the duty cycle [170]; –fairness (implicitly) for Wi-Fi vs. coexistence with itself [159], [161]–[163], [171] –fair coexistence for Wi-Fi as half the throughput of standalone Wi-Fi [171]; –max. network utility with fairness for Wi-Fi as airtime vs. coexistence with itself [173]; –proportional fair rate allocation for Wi-Fi and LTE [147], [174]; –maximize overall throughput with fairness as same airtime for LTE & Wi-Fi [136]; –maximize capacity and minimize Tx power [175] 	<p>–simulations [123], [127], [134]–[136], [140], [147], [149], [159], [161]–[163], [171], [172], [176];</p> <p>–analytical [131], [134], [159], [170], [171], [173]–[175]</p> <p>–measurements [119], [120], [131], [172]</p>	<p>–throughput [119], [120], [123], [127], [131], [135], [136], [140], [147], [149], [159], [161]–[163], [171], [172], [174]–[176];</p> <p>–jitter [119]</p> <p>–delay [147], [159]</p> <p>–SINR [131], [171], [176]</p> <p>–collision probability [171], [174]</p> <p>–throughput fairness [170]</p> <p>–service time fairness [170]</p> <p>–coverage probability [134]</p> <p>–successful links [134]</p> <p>–Jain’s fairness index [162], [163], [173]</p> <p>–airtime [173], [174]</p> <p>–channel utilization [136]</p> <p>–energy efficiency [175]</p> <p>–risk-informed interference assessment [162], [163]</p>	<p>– 1 LTE link/AP & several Wi-Fi devices [119], [120], [147], [170], [171];</p> <p>– ≤15 APs of each technology [123], [127], [131], [136], [140], [159], [173]–[176];</p> <p>– 10–30 APs, or up to 5000 APs/km² of each technology [134], [135], [149], [161]–[163], [172]</p>

performance with fixed duty cycles of 20–100%. The authors found that their scheme enhanced the aggregate Wi-Fi and LTE system capacity.

5) *Wi-Fi/LBT-LTE and Wi-Fi/Duty-Cycle-LTE Coexistence*: Some work in the literature has investigated coexistence with both LBT- and duty-cycle-LTE [123], [134], [135], [147], [149], [159], [161]–[163]. The authors in [147] compared the performance of LBT LBE and CSAT adaptive duty cycle and found that both are equally fair to the Wi-Fi network. Also, for longer LTE transmission time, the LTE throughput for LBT and CSAT was the same. However, this increased the Wi-Fi delay.

The authors in [134] proposed a stochastic geometry model to evaluate: LBT-LTE with random backoff within a fixed interval and different sensing thresholds; and LTE with fixed duty cycle and synchronous/asynchronous muting pattern. The authors found that both LBT and duty cycle could improve Wi-Fi performance compared to Wi-Fi/Wi-Fi coexistence, if LTE adopted either: (i) a low duty cycle; or (ii) LBT with more sensitive sensing thresholds or lower priority than Wi-Fi

when contending for the channel through the random backoff procedure.

In [161] Wi-Fi/LTE coexistence was analysed for LBT with binary exponential random backoff, adaptive duty cycle, and fixed uncoordinated 50% duty cycle. The authors also considered an idealized variant of adaptive duty cycle, i.e. ideal TDMA, where LTE transmissions were scheduled. Different channel selection schemes (i.e. random and least interfered channel), and different transmit power levels were considered. It was show that channel selection is beneficial for Wi-Fi/LTE coexistence, due to the large number of channels in the 5 GHz band. Also, LTE was sometimes a better and sometimes a worse neighbour to Wi-Fi, depending on the sensing threshold and the interference conditions. In [135] this analysis was extended to general coexistence in the unlicensed bands and it was found that adaptive duty cycle was more beneficial in low density scenarios, whereas LBT was better in high density scenarios. The work in [161] was also extended in [162], [163], but by including a new evaluation framework, i.e. risk-informed interference assessment, additionally modelling ACI,

and introducing a fairness metric. The reported results were consistent with those in [161].

Similar findings for similar scenarios as in [122] for LBT-LTE were reported in [123]. However, in [123] the authors also considered LTE with static 50% duty cycle, based on muting LTE subframes with a successive/alternative pattern and synchronously/asynchronously with other LTE BSs.

The authors in [159] focused on fairness when Wi-Fi coexisted with 50% fixed duty cycle LTE, or with 3GPP-based LBT. Fairness was considered to be achieved if LTE degraded the Wi-Fi performance at most as Wi-Fi coexisting with itself would do. The authors reported that none of the mechanisms achieved perfect fairness. However, LBT was preferred to duty cycling.

In [149], brief performance results were presented for LBT based on ETSI FBE (i.e. fixed sensing time) and adaptive duty cycle based on CSAT. The authors found that LTE achieved a higher throughput than when interworking with Wi-Fi (i.e. integrating Wi-Fi into the cellular network), or using the licensed band exclusively.

VI. DISCUSSION

In this section we summarize our literature survey on spectrum sharing mechanisms for wireless inter-technology coexistence, and we indicate open challenges and possible future research directions.

The design of spectrum sharing mechanisms is influenced by both technical and non-technical aspects, such as regulatory restrictions, business models, and social practices. Due to non-technical aspects, implementing the most efficient spectrum sharing mechanisms may not be straightforward. For instance, changes in spectrum regulations were required for TVWS before secondary technologies could share underutilized spectrum with TV services. Another example is the lack of business agreements among network operators, so that information exchange among e.g. different Wi-Fi hotspots operating in the same band may not be possible. Consequently, coordinated spectrum sharing mechanisms cannot be implemented; instead, potentially less efficient, distributed sharing schemes must be used. It is thus critical to **consider the design of spectrum sharing mechanisms for inter-technology coexistence from a unified, system-level perspective that includes both technical and non-technical aspects**. The technology circle considered in this survey represents such a system-level framework, which incorporates Layers 1–7 of the OSI stack, regulatory restrictions at Layer 0, and business models and social practices at Layer 8.

In our literature review in Sections IV and V, we identified three major recent technical and regulatory trends in terms of how spectrum is shared: **(i)** more broadband technologies operating in a spectrum commons, i.e. Wi-Fi/LTE coexistence in the unlicensed bands; **(ii)** introducing multiple primary technologies with equal access rights in the same spectrum band, which is managed by a single entity, e.g. LTE/NB-IoT coexistence; and **(iii)** increasingly more bands set to be open for technologies with primary/secondary access rights, where *secondary/secondary* inter-technology coexistence is also an

issue, e.g. TVWS, the CBRS band, the 2.3-2.4 GHz band with LSA. All three of these major developments represent the case of coexisting technologies with *equal* spectrum access rights, which was the focus of this survey. We note that the spectrum sharing mechanisms considered in the literature for primary/primary and secondary/secondary coexistence resemble either that of traditional, centrally coordinated cellular networks, or that of distributed networks operating in the unlicensed bands, as an instance of a spectrum commons.

Designing spectrum sharing mechanisms for inter-technology coexistence in a *spectrum commons* is the most challenging out of the three identified coexistence cases with equal spectrum access rights, due to the high *heterogeneity* of the coexisting devices. A spectrum sharing mechanism for a technology in such bands has to take into account the (intra-technology) spectrum sharing mechanisms of already existing technologies, but also to anticipate the behaviour of future technologies. This can be addressed through regulatory limitations at Layer 0 for MAC protocols at Layer 2, e.g. ETSI specifying LBT in the 5 GHz unlicensed band in Europe. As a result, 3GPP standardized LAA with LBT to coexist with Wi-Fi in the 5 GHz band. By contrast, no such regulatory limitation on Layer 2 exists in the U.S. for the 5 GHz band, so LTE-U adopted an adaptive duty cycle MAC to facilitate coexistence with Wi-Fi. This was selected due to considerations at Layer 8, i.e. meeting the expectations to protect Wi-Fi [182], while making the minimum changes to the LTE technology, in order to accelerate the time-to-market of commercial deployments.

Importantly, LAA and LTE-U are examples where *inter-technology* spectrum sharing mechanisms also changed the way that *intra-technology* coexistence is achieved; implementing LBT or duty cycling at the MAC layer for LTE enables spectrum sharing with Wi-Fi devices, but also among LTE devices/operators. We emphasize that inter-technology coexistence among more than two wireless technologies has largely not been investigated in the literature yet. Thus far, this was not of practical interest, as Wi-Fi was the only widely-deployed broadband technology in the unlicensed bands, whereas low-traffic technologies did not pose major coexistence problems among themselves. However, studying coexistence among more than two dominant technologies may become important in the near future, due to the increasing heterogeneity of broadband technologies operating in a spectrum commons, e.g. Wi-Fi, LAA, and LTE-U operating in the 5 GHz unlicensed band. Our survey also showed that properly evaluating inter-technology interactions in dense deployments is already complex, even for only two dominant technologies. This opens another valid research question, of whether current methodologies and modelling tools are sufficient to reliably capture the key interactions among multiple dominant technologies in the variety of coexistence cases that may arise.

Our literature review further revealed that, for inter-technology coexistence in a spectrum commons, the preferred spectrum sharing mechanisms are currently the traditional sharing in frequency and time at Layer 2, especially for broadband technologies. Most of the works acknowledged that achieving coexistence through such mechanisms is possible,

e.g. for Wi-Fi/LTE coexistence in the unlicensed bands, but that full optimization is difficult, as this would require information exchange at a level that is not feasible in practice, due to Layer 8 aspects. Moreover, we believe that perfect spectrum sharing optimization for inter-technology coexistence is in general not applicable for a spectrum commons, due to the limited information about other coexisting technologies and devices, the high level of heterogeneity, the large number of network managers, and the dynamics of the deployments; these factors are a direct effect of equal spectrum access rights at Layer 0 and distributed network ownership at Layer 8. Nonetheless, many works in the literature studied inter-technology coexistence with respect to a formal optimization goal, e.g. proportional fairness, despite the potential challenges of implementing such solutions in practice. We emphasize that the validity of these optimum solutions in real (non-idealized) deployments is still an open question, given the variability of system parameters like traffic demand, hardware performance, and network size. An important future research direction is thus performing a thorough sensitivity analysis, to determine the spectrum sharing mechanisms in the design space that are near-optimal yet robust for practical engineering deployments.

In the reviewed literature, Layer 1 spectrum sharing mechanisms were found to be efficient for low-traffic coexisting technologies, e.g. FHSS for Bluetooth. However, Layer 1 techniques such as interference cancellation and beamsteering were found to be less feasible in practice for achieving inter-technology coexistence among broadband technologies. Such techniques are based on acquiring information through multiple wireless interfaces that decode signals of other coexisting technologies. Additionally, interference cancellation also requires changes in the MAC layer. Further research is needed to determine the practical feasibility of achieving inter-technology coexistence via Layer 1 spectrum sharing mechanisms like interference cancellation and beamsteering in large-scale heterogeneous deployments.

We found that comparing the coexistence performance of different candidate spectrum sharing mechanisms is not straightforward, especially given the large amount of research work in the literature, with different assumptions and methods, often referring to different coexistence goals. As evident throughout our literature review, most of the works on inter-technology coexistence, and especially those addressing coexistence in a spectrum commons, focus on evaluating only a single or variants of a given main spectrum sharing mechanism (e.g. variants of LBT-LTE, or duty-cycle-LTE). Moreover, this considered candidate spectrum sharing mechanism is often compared only to the baseline cases where a single technology uses the spectrum, or where newly coexisting technologies do not implement any additional sharing mechanism, e.g. LTE continuously transmitting in the 5 GHz unlicensed band as it traditionally does in dedicated licensed spectrum. Consequently, it is seldom possible to directly compare the coexistence performance reported in different works for different spectrum sharing mechanisms. In order to address this issue, coexistence goals should be more clearly and explicitly defined in the first place. Also, it is important to study candidate spectrum sharing mechanisms for different coexisting technologies

within the same framework.

The recent introduction of different LTE variants as broadband technologies in a spectrum commons suggests that, for capacity increase, operating in unlicensed bands is straightforward to adopt from a technical perspective. These LTE variants aggregate unlicensed carriers, i.e. LAA, and LTE-U, or operate exclusively in the unlicensed bands, i.e. MulteFire [183]. This opens an interesting spectrum regulatory research question: whether it may be attractive to open more shared bands for traffic offloading and reserve licensed spectrum only for important signalling traffic and QoS-guaranteed services.

Finally, we note that most of the reviewed spectrum sharing mechanisms for inter-technology coexistence in a spectrum commons are fully distributed, and only a few centralized, as summarized in Section V and Tables VI and VIII. Considering more fundamental performance limits of inter-technology spectrum sharing mechanisms is still missing from the literature. Specifically, investigating the impact of different levels of coordination among networks of different technologies is a rich yet largely unexplored research direction.

VII. CONCLUSIONS

In this survey we explored the design space of spectrum sharing mechanisms for wireless inter-technology coexistence from a unified, system-level perspective, i.e. the technology circle, that integrates technical and non-technical aspects at different layers. We reviewed the literature on inter-technology coexistence with respect to different layers of the technology circle, where we considered technologies with the same spectrum access rights: (i) primary/primary; (ii) secondary/secondary; and (iii) technologies operating in a spectrum commons. Finally, we identified and discussed spectrum sharing design solutions, performance evaluation approaches, and possible future research directions.

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