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Coexistence of Cellular and IEEE 802.11 Technologies in Unlicensed Spectrum Bands -A Survey

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Abstract- **This paper provides a comprehensive survey on the coexistence of cellular and IEEE 802.11 standards from a holistic viewpoint that takes into account the coexistence of all existing and future cellular and IEEE 802.11 standards in all the available unlicensed spectrum bands. Unlike existing survey works focusing mostly on any unlicensed band and/or standard, we start by giving an overview of unlicensed spectrum bands, including 2.4 GHz, 5 GHz, 6 GHz, and 60 GHz. We then review the operation of cellular technologies, namely Long-Term Evolution Unlicensed (LTE-U), Licensed Assisted Access (LAA), and New Radio Unlicensed (NR-U), worldwide in the unlicensed spectrum bands. Further, we summarize scenarios and categories of coexistence mechanisms, conditions for a fair coexistence, and coexistence-related features. An extensive study on the coexistence mechanisms, deployment scenarios, as well as standardization efforts for the coexistence between cellular and IEEE 802.11 standards, is carried out. Finally, we highlight the coexistence challenges and open problems, the convergence of the Third Generation Partnership Project (3GPP) and IEEE standards, as well as future research directions. Moreover, to provide insights on the relative measures, we also carry out comparative studies of several key concerns with regard to the coexistence, namely unlicensed spectrum band, regulatory requirement, coexistence mechanism, and cellular standardization effort. Each study presents a comparison among potential features of one of these concerns in tabular forms. Finally, we summarize key lessons that are learned and discussed throughout the paper.**

Keywords- Unlicensed band, survey, cellular network, millimeter-wave, coexistence, LTE-U, LAA, NR-U, WiFi, IEEE 802.11.

I. INTRODUCTION

A. *Background*

The demand for high capacity and data rates has increased enormously due to a growth in mobile devices and data traffic over the past years. However, the available licensed spectrum for a Mobile Network Operator (MNO) has not been increased in proportion [1]. To address the scarcity of available licensed spectrum, techniques, including intercell interference coordination, cognitive radio, spatial spectrum reuse, cell splitting, and Small Cell (SC) deployment [2], have been proposed. However, other than any insignificant improvement in the network capacity and data rate per user, no noticeable impact has been observed. This causes the focus to shift from licensed-only spectrum bands to the unlicensed spectrum bands as well due to the availability of a large amount of spectrum in the unlicensed bands (e.g., about 500 MHz spectrum is available in the 5 GHz band). For example, Licensed Assisted Access (LAA) in Long-Term Evolution (LTE) has been proposed by employing the Carrier Aggregation (CA) technology that aggregates both the licensed and unlicensed spectra. Further, since 1997, a number of IEEE 802.11 standards (also referred to as Wireless Fidelity (WiFi) [3]) based technologies have been operating in the unlicensed bands, namely 802.11b/g in the 2.4 GHz, 802.11a/n in the 5 GHz, and 802.11ad/ay in the 60 GHz [4-5].

At present, in addition to 802.11b/g, the 2.4 GHz band is utilized heavily by cordless phones (2.4-2.5 GHz), ZigBee (2.4-2.4835 GHz), and Bluetooth (2.4-2.4835 GHz) technologies [6-10] that provide broadband wireless access in local or personal areas [7]. However, because of being less congested than the 2.4 GHz [7] and the availability of a large amount of spectrum bandwidth (e.g., 500 MHz [3]), the majority of the IEEE 802.11-based technologies operate in the 5 GHz band. Moreover, due to the smaller coverage than that of the 2.4 GHz band, the 5 GHz band is suitable for SCs operating indoors. Besides, in the 6 GHz band, as per the new rules of the Federal Communications Commission (FCC), the unlicensed spectrum operation is considered over most parts of the 5.925-7.125 GHz, and it is expected that Fifth-Generation (5G) New Radio Unlicensed (NR-U) would coexist with the IEEE 802.11 ax/be based systems, i.e., WiFi 6/WiFi 7 [11]. Moreover, due to the availability of a large amount of spectrum bandwidth and being less crowded, the 60 GHz unlicensed band is feasible for bandwidth-intensive services to provide high data and capacity. However, severe oxygen absorption and atmospheric attenuation in the 60 GHz make the physical layer specifications and air interfaces difficult to design [7]. Also, due to the high distant-dependent path loss, the 60

GHz band is considered suitable mostly for indoor coverage [12].

A key feature of the unlicensed bands is that a user of any technology is free to access an unlicensed spectrum band. Moreover, cellular networks, in principle, do not sense the channel condition before any transmission on a licensed band. However, as aforementioned, all these above-unlicensed spectrum bands have been mainly used by WiFi technologies over the past few decades. Hence, to operate cellular technologies in the same unlicensed band at the same place simultaneously, a proper *coexistence* mechanism to manage Co-Channel Interference (CCI) between cellular and WiFi technologies is necessary. Coexistence mechanisms can be developed in two ways depending on whether or not a cellular network is enabled with a carrier sensing mechanism, termed as Listen-Before-Talk (LBT). LBT is a contention-based medium access technique similar to the Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism used by WiFi [13] that shares a channel between a cellular node (i.e., Base Station (BS)) and a WiFi Access Point (AP) fairly [7] by enabling a cellular node to stop periodically its channel occupancy and to detect the activities of other shared nodes [7] to help avoid CCI due to the coexistence.

However, the LBT coexistence mechanism is not mandatory to apply in all regions (e.g., the USA and China) and standards (e.g., LTE Unlicensed (LTE-U)) [13]. Since cellular nodes cannot sense the channel activity, and LTE-U is not LBT enabled, LTE-U causes CCI when accessing the shared channel by WiFi APs. Hence, a new coexistence mechanism is needed for standards like LTE-U to allow WiFi APs to get access to a shared channel. Numerous coexistence mechanisms without employing LBT have been proposed by exploiting different domains to manage CCI, particularly, Channel Selection (CHS) in frequency-domain, Carrier Sense Adaptive Transmission (CSAT), and Fully Blank Subframe (FBS) in time-domain, and Transmit Power Control (TPC) in power-domain.

B. *Related Study*

Numerous surveys [3], [13-17] have already been carried on the coexistence of cellular and IEEE 802.11 standards taking into account one or more of the following aspects, including the unlicensed spectrum band, cellular and/or IEEE 802.11 standard, coexistence mechanism, deployment scenario, transmission technique, regulatory requirement, design principle, potential issue, existing solution, and roadmap for future research.

More specifically, concerning the coexistence of LTE systems in the 5 GHz unlicensed bands, the authors in [14] studied LTE-LAA and WiFi coexistence in the 5 GHz with the corresponding deployment scenario and scenario-oriented decision-making. Moreover, the authors in [3] provided a comprehensive survey on various coexistence scenarios in the 5 GHz bands. The authors discussed coexistence issues between LTE and WiFi, radar and WiFi, dedicated short-range communication and WiFi, as well as coexistence among various 802.11 protocols, operating in the 5 GHz bands. Similarly, in [15], the authors presented a comprehensive coexistence study of WiFi and LTE-in-unlicensed by surveying a large parameter space of coexistence mechanisms and a range of representative network densities and deployment scenarios and showed that harmonious coexistence between WiFi and LTE is confirmed by the large number of 5 GHz channels. Besides, the authors in [16] gave a comprehensive analysis of the physical layer design principles of cellular communication systems on the unlicensed spectrum considering applications in the LTE-LAA system.

Concerning the coexistence of NR-U systems in unlicensed bands, in [13], emphasizing unlicensed Millimeter-Wave (mmWave) bands, as well as considering the beam-based transmissions and the worldwide regulatory requirements, the authors presented an overview of the major design principles and solutions to operate NR-U in unlicensed bands. Likewise, the authors in [17] provided a survey on various issues related to operating (unlicensed Radio Access Technologies (RATs) such as WiFi and NR-U in the USA and Europe) in the 6 GHz unlicensed bands by discussing key features in the next-generation WiFi being designed to leverage the 6 GHz unlicensed bands, as well as highlighting key research problems due to the operation in the 6 GHz bands.

C. *Contribution*

Different from these above existing surveys, in this paper, we provide a survey on the coexistence of cellular and IEEE 802.11 standards from a holistic viewpoint that takes into account the coexistence of all existing and future cellular and IEEE 802.11 standards in all available unlicensed spectrum bands. In particular, the paper reviews diversified concerns for the coexistence of cellular and IEEE 802.11 standards, including coexistence-related feature, mechanism category, coordination, fairness condition, transmission technique, regulatory requirement, deployment scenario, standardization effort, challenge, open problem, convergence, and future research direction. Besides, to provide relative measures, we also carry out comparative studies of several key concerns, namely unlicensed spectrum band, regulatory requirement, coexistence mechanism, and cellular standardization effort, each presenting a comparison among potential features of one of these concerns in tabular forms. More specifically, we contribute the following in this paper.

- We first give an overview of unlicensed spectrum bands, including 2.4 GHz, 5 GHz, 6 GHz, and 60 GHz. A comparison among these unlicensed bands is then presented in a tabular form. We also review the operation of cellular technologies, namely LTE-U, LAA, and NR-U, worldwide in the unlicensed spectrum bands.

- Secondly, we then discuss scenarios and categories of coexistence mechanisms, conditions for fair coexistence, and coexistence-related features. A comparison between regulatory requirements to operate in the 5 GHz and 60 GHz bands are also presented because of worldwide availability.
- Thirdly, an extensive study on coexistence mechanisms with employing LBT, as well as without employing LBT (e.g., with employing CHS, CSAT, FBS, and TPC), on existing cellular networks is carried out followed by presenting a comparison of these coexistence mechanisms for cellular and IEEE 802.11 technologies.
- Fourthly, we discuss coexistence deployment scenarios for LTE-U, LAA, and NR-U, as well as standardization efforts toward the coexistence between cellular and IEEE 802.11 standards.
- Fifthly, we point out relevant coexistence challenges and open problems, discuss the convergence of the Third-Generation Partnership Project (3GPP) and IEEE standards, as well as highlight noticeable future research directions.
- Finally, we summarize key lessons that are learned and discussed throughout the paper.

To demonstrate the position of this survey paper as compared to the existing ones, a comparison of the existing survey works discussed in section I(B) with respect to this paper is given in Table I.

D. *Organization*

We organize the paper in different sections as follows. Section II covers the overview of unlicensed spectrum bands, as well as the operation of cellular technologies in the unlicensed bands. In section III, scenarios and categories of coexistence mechanisms, coexistence fairness conditions, as well as coexistence-related features, are discussed. A comprehensive discussion on coexistence mechanisms is covered in section IV. Section V discusses coexistence deployment scenarios for cellular standards, as well as standardization efforts toward the coexistence. Coexistence challenge and open problem, the convergence of 3GPP and IEEE standards, and future research directions are pointed out in section VI. The lessons that are discussed throughout the paper and derived from this survey are summarized in section VII. We conclude the paper in section VIII. A list of abbreviations is given in Appendix I.

II. UNLICENSED SPECTRUM BANDS AND OPERATION OF CELLULAR TECHNOLOGIES

A. *Overview of Unlicensed Spectrum Bands*

Unlicensed bands, including 2.4 GHz, 5 GHz, and 6 GHz bands (also termed as sub-7 GHz bands) in the low-frequency range, as well as 60 GHz mmWave band in the high-frequency range, are approved for the operation of cellular technologies. An overview of each of these unlicensed bands is given below.

1) 2.4 GHz: The 2.4 GHz band is the first unlicensed band released by the FCC for commercial use and is currently the most utilized unlicensed shared band [7]. In the 2.4 GHz band, the bandwidth is divided into 14 channels with a separation of 5 MHz from one channel to another. In the USA, operations on channels 12 and 13 are allowed only under low power conditions [18]. Likewise, in Canada, of a total of 12 channels (from channel 1 to channel 12) available to use, the operation on channel 12 is limited by the transmission power. However, most of the rest of the world can use 13 channels (from channel 1 to channel 13) [18], and channel 14 is available only in Japan as shown in Fig.1.

2) 5 GHz: The use of the 5 GHz band depends on its requirement in a country [14]. Figure 1 shows the use of the 5 GHz unlicensed spectrum by numerous countries. As it can be seen that the 5.15-5.35 GHz (Unlicensed National Informational Infrastructure (UNII)-1 and U-NII-2A) band is available in the USA, China, South Korea, Europe, Japan, and India; the 5.47-5.725 GHz (U-NII-2C) is available in the USA, South Korea, Europe, and Japan; and the 5.725-5.85 GHz (U-NII-3) is available in the USA, China, South Korea, and India [3]. Hence, in the USA and Canada, the 5.15-5.35 GHz and 5.47-5.85 GHz unlicensed spectra can be used for wireless access [7]. However, in Europe and Japan, the 5.15-5.35 GHz and 5.47-5.725 GHz unlicensed spectra are available for the Wireless Access System (WAS), as well as Radio Local Area Networks (RLANs). Further, the 5.15-5.35 GHz spectrum for indoors and the 5.725-5.85 GHz spectrum for both indoors and outdoors can be used in China [7].

Additionally, the 5.35-5.47 GHz (U-NII-2B) and the 5.85-5.925 GHz (U-NII-4) unlicensed spectra are being considered to make available in the USA and Canada [3], [6-7]. For example, a Notice of Proposed Rulemaking (NPRM) 13-22 [19] issued by the FCC of the USA in 2013 proposed to open up an additional spectrum of 195 MHz in the 5.35-5.47 GHz that merges with a number of radar systems bands and the 5.85-5.925 GHz that merges with the spectrum assigned with Intelligent Transportation Systems (ITSs) bands [3]. Moreover, European Commission also recently proposed to use 5.725-5.85 GHz spectrum (currently used for the Fixed Wireless Access (FWA)) for WAS/RLANs [7]. In general, due to the clearer channel condition, wider spectrum, and easier implementation [7], the 5 GHz band is considered favorable to other unlicensed bands.

3) 6 GHz: The 6 GHz spectrum is available from 5.925 to 6.425 GHz in Europe, whereas from 5.925 to 7.125 GHz in the USA [17]. Recently, 5.925-6.425 GHz [20] spectrum and 5.925 GHz-7.125 GHz spectrum have been proposed, respectively, by the European Commission (EC) and the

FCC under part 15 rules for the unlicensed access [21-22]. Hence, the amount of the unlicensed spectrum available in Europe is 500 MHz and in the USA is 1200 MHz, which can help address the high capacity demand of future mobile networks. Also, in the USA, the 6 GHz band is considered to be divided further into four sub-bands, namely U-NII-5 in the range of 5.925-6.425 GHz, U-NII-6 in the range of 6.425-6.525 GHz, U-NII-7 in the range of 6.525-6.875 GHz, and U-NII-8 in the range of 6.875-7.125 GHz [17]. In the Americas, like the USA, Brazil, Chile, and Guatemala have also recently opened up all 1200 MHz of the 6 GHz band

TABLE I
A COMPARISON OF THIS PAPER WITH EXISTING SURVEY WORKS.

Survey work	**Contribution**
[3]	A comprehensive overview of the various coexistence scenarios in the 5 GHz bands. The following coexistence issues in the 5 GHz bands are discussed in the paper. • wireless technologies in the 5 GHz bands; • coexistence of LTE and WiFi; • coexistence of radar and WiFi; • coexistence of Dedicated Short-Range Communications (DSRC) and WiFi; • coexistence between heterogeneous WiFi technologies.
[13]	A complete overview of the major design principles and solutions for NR-U operation in unlicensed bands, with an emphasis on mmWave bands, by taking into account the beam-based transmissions and the worldwide regulatory requirements. The following are discussed in the paper. • spectrum allocation and regulatory requirements; • NR-U scenarios and LBT specifications; • from NR to NR-U; • channel access procedures for NR-U; • Channel Occupancy Time (COT) structure for NR-U; • initial access procedures for NR-U; • Hybrid Automatic Repeat Request (HARQ) procedures for NR-U; • scheduling methods for NR-U; • evaluate the performance of different LBT-based channel access procedures; • lessons learned and future perspectives.
[14]	A comprehensive survey of the coexistence of LTE-LAA and WiFi on 5 GHz with corresponding deployment scenarios. The authors mainly address the following in the paper. • analysis on coexistence-related features of LTE-LAA and WiFi; • current research on LTE-LAA and WiFi coexistence considerations; • deployment scenarios for the coexistence and scenario-oriented decision-making; • challenges and further research directions.
[15]	A comprehensive coexistence study of WiFi and LTE-in-unlicensed, surveying a large parameter space of coexistence mechanisms and a range of representative network densities and deployment scenarios. The following are addressed in the paper. • methodology and scenarios, including entrant technologies and coexistence mechanisms, as well as deployment scenarios; • simulation and throughput models; • results, including the typical impact of the entrant on the existing WiFi, the typical impact of LTE-in-unlicensed entrant technologies, and • the worst-case impact of the entrant on WiFi.
[16]	A comprehensive analysis of the physical layer design principles of cellular communications on the unlicensed spectrum with applications in the LTE system (i.e., LTE-LAA). The paper emphasizes the following. • unlicensed spectrum and regulatory requirements; • baseline LBT framework for cellular systems; • practical systems (LTE-U and LTE-LAA); • future research.
[17]	A comprehensive survey of the existing literature on various issues surrounding the operations of unlicensed RATs in the 6 GHz bands. The authors discuss the following in the paper. • benefits of the 6 GHz spectrum; • coexistence with existing technologies; • coexistence among unlicensed technologies; • adjacent channel interference issues; • research challenges.
This paper	A comprehensive survey on the coexistence of cellular and IEEE 802.11 standards from a *holistic viewpoint* that takes into account the coexistence of *all* existing and future cellular and IEEE 802.11 standards in all the available unlicensed spectrum bands. • unlicensed spectrum bands and operation of cellular technologies; • condition for fair coexistence, as well as coexistence related features, scenarios, and categories; • coexistence mechanisms; • coexistence deployment scenarios and standardization efforts; • coexistence challenge, open problem, convergence, and future research direction.

for unlicensed use [23]. In Asia, South Korea has recently announced the near future unlicensed use of 1.2 GHz (5.925 to 7.125 GHz) in the 6 GHz band [24].

In the USA, due to the existence of ITSs' band spanning over 5.85-5.925 GHz, adjacent to the 6 GHz [17], the ITS band needs to be protected from the 6 GHz band. Moreover, to avoid interference with radars and other licensed services in the U-NII bands, unlicensed users need to perform Dynamic Frequency Selection (DFS) [11]. In this regard, if a radar signal is detected, the transmission needs to be stopped within 10 seconds and the channel needs to be given up for 30 minutes [11]. Since much of the 6 GHz band is occupied by some licensed services, such as microwave links, fixed satellite systems, and mobile services, Automatic Frequency Coordination (AFC) is needed only in the U-NII-5 and U-NII-7 bands [11] by unlicensed users to protect licensed services.

Besides, unlicensed users are also required to control their transmit power and restrict their coverage to indoors [11]. In the USA, Low Power Indoor (LPI) is authorized over all 1200 MHz, and Very Low Power (VLP) operation is still subjected to a very active rulemaking process. An LPI device is required to operate indoors at about four times lower power than that of a standard WiFi device, whereas a VLP device may operate both indoors and outdoors at 160 times lower power than that of a standard WiFi device [25]. In Europe, both LPI and VLP (without any outdoor operation) are approved to operate across 500 MHz [23]. South Korea has permitted LPI to operate across all 1200 MHz, whereas VLP devices across 500 MHz only. Chile and Guatemala have permitted LPI to operate across all 1200 MHz [23]. However, in Brazil, both LPI and VLP devices are authorized to operate across all 1200 MHz making it the first country that approves VLP universally across the band [26].

4) 60 GHz: The 60 GHz band is considered for the NR-U to provide directional communications using beamforming to overcome propagation constraints, including high distant-dependent path loss, blocking, and oxygen absorption [27-28]. Due to operating IEEE 802.11 ad/ay (i.e., Wireless Gigabit (WiGig)) in the 60 GHz band, NR-U needs to coexist fairly with the WiGig standard. However, the beam-based directional transmissions of NR-U make the coexistence with WiGig more challenging than that of the omnidirectional transmissions/receptions in WiFi and LTE coexistence [13].

Note that the 60 GHz band ranges from 57 GHz to 71 GHz [29] of which 9 GHz in Europe and 14 GHz in the USA are available, which are, respectively, 10 times and 16 times more unlicensed spectrum than that in the sub-7 GHz band [30]. In IEEE 802.11ad, the 60 GHz band is divided equally into six sub-bands each occupying 2160 MHz with an effective bandwidth of 1760 MHz [29]. The bandwidth available in the unlicensed 60 GHz band is more than that of the aggregate bandwidth of all the other unlicensed bands [31].

Table II shows the 60 GHz unlicensed spectrum available worldwide [29]. The minimum available bandwidth in a region is more than 3 GHz, and at least 7 GHz of bandwidth can be used in most regions in the 60 GHz band in comparison with just about 500 MHz of usable bandwidth in the 5 GHz band and less than 85 MHz of bandwidth in the 2.4 GHz band in most regions [31]. Due to this reason, the 60 GHz band is suited for serving high data rate demand in magnitudes of Gbps over short distances.

B. Cellular Technologies in the Unlicensed Spectrum Bands

The operation of the 3GPP-based cellular technologies in the unlicensed bands has recently been introduced. Cellular technologies may operate in one or more unlicensed spectrum bands, including 2.4 GHz, 5 GHz, 6 GHz, and 60 GHz. Because the operation of the unlicensed spectrum is marked by regional regulatory authorities [6], of these, 2.4 GHz, 5 GHz, and 60 GHz bands are available worldwide [32], whereas the 6 GHz band is currently available in Europe and the USA. In addition to these above-unlicensed bands, cellular technologies, particularly, 5G NR-U can also use shared bands, including 3.5 GHz and 37 GHz, only in the USA [13]. Note that 2.4 GHz, 3.5 GHz, 5 GHz, and 6 GHz are classified as low-frequency bands below 7 GHz, whereas 37 GHz and 60 GHz high-frequency bands are classified as mmWave bands. These two frequency ranges are targeted for 5G NR-U operations [11]. Since cellular technologies in the previous generations, specifically, Fourth-Generation (4G) LTE, were not allowed to use mmWave bands, LTE-U and LAA operate in the 5 GHz band.

LAA is developed by the 3GPP using the CA-based deployment mode and an LBT-based channel access scheme [33-34]. LTE-U is developed by the LTE-U Forum using the CA-based deployment mode and employing a policy such as the orthogonal transmission of coexisting nodes, mainly in frequency and time domains [35-37], with channel access schemes, including fully blank subframes and duty cycles (instead of an LBT) [38]. NR-U is also being developed by the 3GPP with a native feature to operate in unlicensed bands in Release 16 [13] [39]. Unlike LTE that operates only in the 5 GHz unlicensed spectrum, NR-U can operate on multiple spectrum bands, including mmWave bands, e.g., sub-7 GHz and 60 GHz [32]. In addition to the CA, other deployment modes such as dual connectivity and standalone operation in the unlicensed bands are also considered for NR-U. Moreover, like LTE, there are a number of variants of 5G NR-U, including 5G NR-U Standalone operating only in an unlicensed spectrum band (e.g., 60 GHz) and 5G NR-U Anchored operating in both the licensed spectrum and the 60 GHz unlicensed spectrum. However, *MulteFire* is developed by the MulteFire Alliance considering a Standalone deployment in the unlicensed bands (without employing the CA-based deployment mode) and using an LBT-based channel access scheme [47].

Note that LTE is the first cellular-based technology extended with a view to operating in the 5 GHz unlicensed spectrum in 2015, whereas NR-U is the first cellular-based technology that includes operations in the mmWave unlicensed bands [13], [32]. Moreover, LTE radio equipments operating in the 5 GHz unlicensed spectrum in a region need to satisfy certain regional regulatory requirements, including indoor-only use, maximum in-band output power, in-band power spectral density, out-of-band and spurious emissions, DFS, and TPC [34].

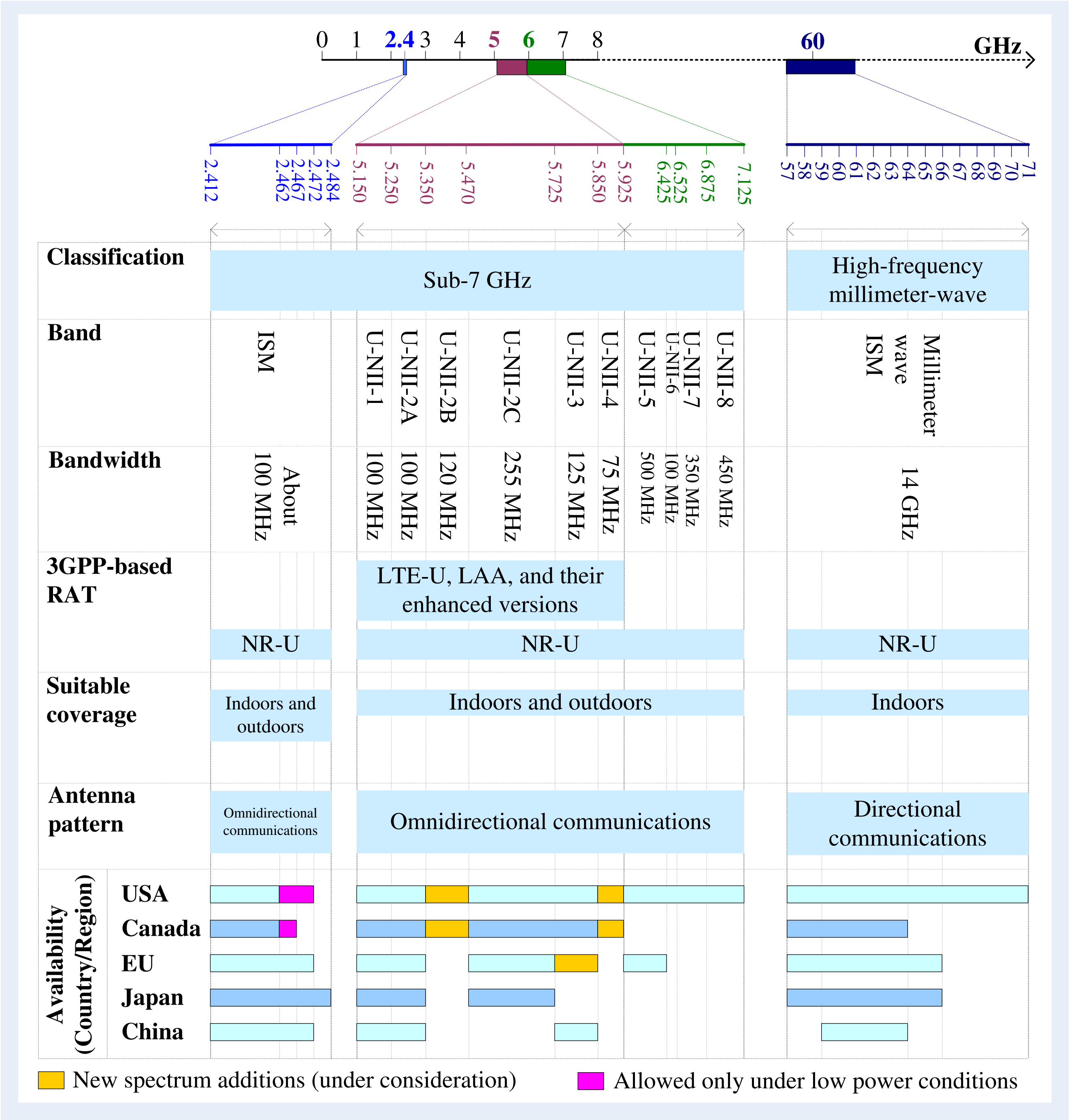

Fig. 1. Unlicensed spectrum bands for cellular technologies worldwide [3], [7], [11], [13]. Note that though we mention indoors and outdoors regarding the suitable coverage for the operation of the sub-7 GHz for simplicity, it actually depends on regional regulations, e.g., bands such as U-NII-6 and U-NII-8 are used currently indoors only in the USA. Moreover, the term U-NII is used only in the USA.

TABLE II
A COMPARISON AMONG 2.4 GHZ, 5 GHZ, 6 GHZ, AND 60 GHZ UNLICENSED BANDS [29], [34].

Features	**Unlicensed spectrum bands**			
	2.4 GHz	**5 GHz**	**6 GHz**	**60 GHz**
Classification	Mid-bands (sub-7 GHz)			High-bands (mmWave)
Availability	Worldwide		Europe and the USA	Worldwide
Regulatory requirement	The maximum data rate, multiple access method, (spread spectrum / Orthogonal Frequency-Division Multiplexing (OFDM)), digital modulation scheme, maximum coverage distance, and media access protocol (collision avoidance technique) [40]	Indoor-only use, maximum in-band output power, in-band power spectral density, out-of-band and spurious emissions, DFS, LBT, and TPC [34]	DFS, AFC, TPC, and indoor coverage [11]	Short-range communication, Equivalent Isotropic Radiated Power (EIRP), EIRP densities, the maximum conducted power, and the maximum and minimum antenna gains [41-42]
Existing technologies [43], [13]	802.11b/g, 802.11n/ax, ZigBee, Bluetooth, and cordless phones	802.11a, 802.11n/ax, 802.11ac	802.11ax, Licensed microwave links, fixed satellite systems, and mobile services	802.11ad/ay
Cellular technologies	NR-U	LAA, LTE-U, MulteFire, and NR-U	NR-U	
3GPP Releases	Release 16 (5G NR-U)	Release 10/11/12 (LTE-U), Release 13 (LAA), and Release 16 (5G NR-U)	Release 16 (5G NR-U)	
Available bandwidth [3]	About 80 MHz	500 MHz [3]	500 MHz (Europe) and 1200 MHz (USA) [21-22]	9 GHz (Europe) and 14 GHz (the USA)
Minimum available bandwidth in most regions	Less than 85 MHz [31]	About 500 MHz [31]	500 MHz [21-22]	At least 7 GHz [31]
Suitable coverage	Indoors and outdoors			Indoors
Spectrum range	2.40-2.50 GHz [9]	5.150-5.925 GHz [3]	5.925-7.125 GHz [13]	57-66 GHz [31]
Antenna pattern	Omnidirectional [21]			Directional [44-45]
Constraints	• Heavily congested • lower data rate • more susceptible to interference • more devices per unit frequency than that in 5 GHz or 6 GHz [46]	• Lower coverage (with respect to that of the 2.4 GHz band) • Higher penetration and path losses • Less prone to interference than that in 2.4 GHz [46]		• Extremely high penetration and path losses • Blocking • Oxygen absorption [27-28]
Advantages	• Most utilized unlicensed shared band • Favorable signal propagation characteristics due to the low frequency.	• Less congested and interfered than the 2.4 GHz [7], • Availability of a large amount of spectrum bandwidth (e.g., 500 MHz [3]), • The majority of IEEE 802.11-based technologies operate in the 5 GHz band, and • Suitable for SCs operating indoors.	• Unlike 5 GHz, there is no need to align channel access protocols for the LTE-LAA with those used by WiFi devices in the 6 GHz band where no unlicensed devices now operate [17]. • Indoor operations are permitted by default [17]. • The high capacity demand of future mobile networks can be addressed.	• Large spectrum bandwidth availability • Line-Of-Sight (LOS) signal components • High capacity and data rates at a short distance indoors.

Table II shows the regulatory requirements for various regions that need to be satisfied when operating in the 2.4 GHz, 5 GHz, 6 GHz, and 60 GHz unlicensed spectrum [34]. Though existing IEEE and 3GPP-based technologies operate in the unlicensed bands on a competitive basis, such competition results in convergence to use and develop similar features in the radio access in the latest releases and amendments [32], e.g., the use of LBT to 3GPP technologies developed in line with CSMA/CA inherent to the IEEE 802.11 technologies. The convergence in IEEE 802.11 and 3GPP-based technologies results in efficient design and supporting operation in large bandwidth [32].

The above discussion on the unlicensed bands is summarized in Table II by showing comparisons in terms of numerous aspects among 2.4 GHz, 5 GHz, 6 GHz, and 60 GHz unlicensed spectrum bands. Further, Fig. 1 [11] shows an illustration of the operations of these unlicensed spectrum bands. Hence, a total of about 2 GHz unlicensed spectrum bandwidth is available below 7 GHz for omnidirectional communications at the 2.4 GHz and the

UNII bands at 5 GHz and 6 GHz frequencies [21]. Moreover, a large amount of 9 GHz of spectrum in Europe and 14 GHz unlicensed spectrum in the USA is available in the 60 GHz band for directional communications [44-45]. Note that the 5 GHz band is divided into non-overlapping channels of 20 MHz. Wider channels such as 40, 80, …, can be constructed via channel bonding [11].

III. COEXISTENCE SCENARIO, CATEGORY, FAIRNESS, AND RELATED FEATURE

A. *Scenarios and Categories of Coexistence Mechanisms*

A *coexistence scenario* incorporates two or more wireless networks or users that hamper their performances mutually by affecting the operation of one to another when accessing the same spectrum band [48]. Based on the exchange of messages between networks, coexistence scenarios can be categorized into two, namely uncoordinated and coordinated schemes [49-50].

In an *uncoordinated* scheme, one network can coexist autonomously with another without any coordination. Uncoordinated networks typically implement their coexistence mechanisms on their own without any discussion with the others and hence are mostly based on their local observations to adapt to the dynamics of the coexistence setting [48]. Since it does not require any infrastructure or change in current networks [48], most existing schemes are uncoordinated. However, the simplicity in uncoordinated schemes might require more sophisticated coexistence schemes since each network needs to identify first the existence of another network, followed by its operational parameters [51]. For example, to accurately understand the co-channel activity of WiFi networks, an LTE-U network needs to decode WiFi packets [48].

In contrast, in a *coordinated* scheme, networks usually have a mutual agreement on parameters used among them by coordinating directly or indirectly with each other. In coordinated schemes, networks usually have the infrastructure to exchange information among themselves. Coordinated schemes can be implemented both centrally (e.g., using Software Defined Networking (SDN) [48]) and in a decentralized manner (e.g., via a direct communication channel). A common control/management plane may be required between networks. Moreover, to gain advantage from the coordination, a Cross-Technology Communication Channel (CTC) is used to provide information about the identity of the interferer networks, as well as the level of mutual interference, for example [48]. Even though coordinated schemes suffer from higher protocol/ infrastructure complexity and coordination overhead, they benefit from better performance than that of uncoordinated schemes [52-53] due to being able to declare networks' requirements and operation parameters explicitly. Coordinated schemes are suitable for the same type of networks such as two or more NR-U networks [54] in contrast to uncoordinated schemes, which are suitable for different types of networks such as NR-U and WiFi networks.

B. *Condition for Fair Coexistence*

Fairness is one the most striking points for the coexistence studies as there is no legal documental agreement on a definition of fairness. A major concern that defines the degree of coexistence performance is the condition for *fair coexistence* among different types of networks. This is because cellular and WiFi networks use different Medium Access Control (MAC) layer policies. For example, cellular networks such as LTE and 5G NR are centralized scheduling-based that transmit data continuously. This may, however, block the channel resulting in depriving WiFi APs to access the channel. Hence, to help protect WiFi nodes from not being channel blocked by cellular nodes, a fair and effective coexistence between cellular nodes and WiFi APs is necessary when accessing the same unlicensed spectrum.

Though there is no concrete definition for fair coexistence, according to the 3GPP, the fair coexistence between a cellular network such as LTE and an IEEE 802.11 network such as WiFi is defined as follows.

The capability of an LAA network not to impact WiFi networks active on a carrier more than an additional WiFi network operating on the same carrier, in terms of throughput and latency [55-56].

Likewise, for NR-U, the coexistence requirement with WiFi/WiGig remains the same as that in LAA such that the existence of an NR-U network cannot impact the performance of WiFi/WiGig more than an additional WiFi/WiGig network would do [39]. However, it is to be noted that many 3GPP members might believe that fairness means cellular nodes and IEEE 802.11 APs should have half of the bandwidth.

C. *Coexistence Related Features*

To understand coexistence mechanisms between the cellular and the IEEE 802.11 technologies, knowledge about the coexistence-related features of both technologies are crucial as given in the following.

1) Operating in both licensed and unlicensed bands: Due to the nature of being unlicensed, it is difficult to ensure guaranteed Quality-of-Service (QoS) by operating only on the unlicensed bands [7]. This justifies the availability of a licensed band in addition to operating on the unlicensed bands for cellular technology. Due to this reason, 3GPP initiated LAA as part of Release 13 [57-58] so that a user can get access to both licensed and unlicensed bands.

2) CA with unlicensed bands: In cellular technology such as LTE-Advanced, to extend the available spectrum bandwidth, 3GPP developed the CA technology to aggregate more than one contiguous or non-contiguous component carrier. Similarly, 3GPP employed the CA technology on LAA to aggregate a licensed spectrum band with an unlicensed band [59-62]. For example, LAA operating on the spectrum of a licensed band can aggregate with the spectrum of the 5 GHz unlicensed band to extend its available spectrum bandwidth.

3) Channel access mechanism: Since cellular technologies do not listen to the channel condition when scheduling resources and the IEEE 802.11 technologies use the contention-based protocol to access a channel, it is not unusual that the cellular nodes may block transmission of WiFi APs completely when operating in the same WiFi unlicensed spectrum. Hence, to overcome this issue, CSMA/CA-like protocol in WiFi, also called LBT, needs to be implemented with cellular nodes to get access to an unlicensed channel to meet the regulatory requirements worldwide. In this regard, LAA supports the LBT mechanism [14] along with the CA technology to become a global standard.

4) MAC protocols: Cellular technology is an allocation-based mechanism, whereas WiFi technology is a contention-based mechanism. Cellular technology uses continuous transmission of data in consecutive frames using a centralized schedular located mainly in the macrocell BSs. However, WiFi technology uses opportunistic transmission using Distributed Coordination Function (DCF). DCF is a contention-based mechanism [7] that uses the CSMA/CA protocol to detect the energy level in order to get access to a channel.

In CSMA/CA [63-64], a WiFi device senses the channel first to detect if any other WiFi device is occupying the channel before sending its data to avoid the collision with the existing occupant. If the WiFi device finds that the channel is idle, it can start transmitting its data over the channel. Otherwise, it selects a random back-off timer so that it starts its transmission only when the timer decreases to zero [63-64]. Due to the CSMA/CA behavior, once WiFi devices gain channel access, they occupy the entire bandwidth for a certain duration of time. However, in cellular technology such as LTE, the available spectrum bandwidth is not shared between its users. Rather, the bandwidth is first divided into Resource Blocks (RBs), which are then allocated to its users at each Transmission Time Interval (TTI) by a centralized scheduler [65]. A centralized schedular is an Evolve Node B (eNodeB) in the case of LTE.

Due to these disparities given above in the MAC layer procedures, the coexistence between different RATs is difficult. Besides, as mentioned earlier, if cellular and WiFi networks operate at the same frequency and location, WiFi APs may get blocked by a cellular network. Likewise, if WiFi APs can get access to a channel, they can cause interference to a cellular network since WiFi packets are transmitted always with the maximum power. In this regard, to avoid the interference between any WiFi AP and cellular node, based on the regulatory requirements, mechanisms such as LBT and CSAT, discussed in detail in the following sections, can be applied.

5) Design principle: Cellular technology such as LTE is designed with an assumption that each mobile network operator has exclusive access to its licensed/allocated spectrum. Irrespective of the presence of data traffic, LTE continuously transmits with a small-time gap, as well as periodically. However, IEEE 802.11 technology, i.e., WiFi, is designed to coexist with other technologies through random backoff and channel sensing, which allows WiFi APs a little chance to sense a clear channel and transmit. Overall, due to the presence of the CSMA/CA protocol, a WiFi AP moves to the silence mode causing its performance degradations, while any LTE node remains almost unaffected [14].

6) Regulatory requirements: Regulatory requirements to operate different cellular technologies in the unlicensed bands vary from one country/region to another. For example, though countries such as the USA, China, India, and South Korea [14] do not require cellular technologies such as LTE to be LBT enabled, LBT is mandatory in Japan and Europe. Hence, of the two variants of LTE operating in the unlicensed bands, LTE-U and LAA, LTE-U does not implement the LBT mechanism so that LTE-U can be used in the USA, China, India, and South Korea. However, as LAA is LBT enabled, LAA can be used worldwide [14].

In general, because fewer modifications are required from the licensed LTE to implement LTE-U than that required to implement LAA, several countries as aforementioned relax the enforcement of LBT to the licensed LTE in the initial commercial deployments of LTE in the unlicensed band. However, later releases to LTE-U are expected to be implemented with LBT for fair coexistence with IEEE 802.11 technologies. Moreover, to ensure worldwide regulation-compliant unlicensed spectrum access and fair coexistence, any technology that would like to operate in the unlicensed band should fulfill the following regulatory requirements [13]. Because 5 GHz and 60 GHz unlicensed bands are available worldwide [13], we limit our discussion to the regulatory requirements of 5 GHz and 60 GHz, which are given in Table III in the following.

7) Modifications in the existing cellular technologies: Because LBT works like CSMA/CA of WiFi technologies, major modifications in the channel access mechanism in the existing cellular technologies are required. However, the coexistence with IEEE 802.11 technologies can also be performed without implementing LBT. More specifically, by exploiting time, frequency, and power domains [6], the co-channel interference between cellular nodes and WiFi APs can be avoided or mitigated. For example, blank subframe allocation and CSAT mechanisms in time-domain, channel selection mechanism in frequency-domain, and

TABLE III

REGULATORY REQUIREMENTS TO OPERATE IN THE 5 GHZ AND 60 GHZ BANDS.

Regulatory Requirement		**5 GHz**	**60 GHz**
LBT	Mandatory	Japan and Europe	
	Based on	Channel energy detection	
	LBT mechanism and parameter for each band [66-67]	Clear Channel Assessment (CCA) slot duration is 9μS	CCA slot duration is 5μS
	Energy detection threshold	-42 dBm for a 20 MHz	-47 dBm for a 40 MHz
Maximum Channel Occupancy Time (MCOT)	Transmission	Continuous transmission is prohibited	
	MCOT	2ms, 4ms, and 6ms and can increase up to 8-10 ms [67]	9 ms [66]
EIRP, and power spectral density	Maximum mean EIRP and Power Spectral Density (PSD)	• 23 dBm and 10 dBm/MHz (for 5.15-5.35 GHz) [67] • 30 dBm and 17 dBm/MHz (for 5.47-5.725 GHz) [67]	40 dBm and 13 dBm/MHz [66]
Occupied Channel Bandwidth (OCB)		Between 70% and 100% of the Nominal Cannel Bandwidth (NCB) [67]	Between 80% and 100% of the NCB [66]
DFS		If radar signals are detected, a device should switch to another channel to avoid interference	

transmit power control mechanism in power-domain can be employed for the coexistence. Note that these coexistence mechanisms can be applied to LTE-U in regions where LBT is not mandatory. A detailed discussion on each coexistence mechanism is given in the following sections.

8) Energy detection threshold: In LBT operation, the Energy Detection (ED) threshold of the shared channel plays an important role in deciding the channel occupancy flexibly to by either cellular node or WiFi. If the energy is beyond higher than the threshold, the cellular node assumes that the channel is busy. Otherwise, it transmits traffic using the shared channel.

IV. COEXISTENCE MECHANISMS

Since cellular networks do not sense the channel condition before any transmission, when operating in an unlicensed band, they cause interference to the existing WiFi networks. Such interference due to the coexistence can be avoided in mainly two ways as follows depending on whether or not existing cellular networks are allowed to enable with a CSMA/CA-like carrier sensing mechanism, termed as LBT.

- Approach 1: Cellular networks with employing the LBT mechanism and
- Approach 2: Cellular networks without employing the LBT mechanism.

However, recently, the Game Theory (GT) paradigm has gained attention as a good alternative to address coexistence between cellular (e.g., LTE-U) and IEEE 802.11 (e.g., WiFi) technologies [68-70]. Hence, in addition to approaches 1 and 2, we also discuss the GT-based solutions regarding the coexistence between cellular and IEEE 802.11 technologies.

A. Approach 1: Cellular Networks with Employing the LBT Mechanism

In this case, a cellular network, e.g., LTE, is enabled with the LBT mechanism, which can help avoid interference with other existing transmissions by backing off or moving to another channel using the DFS technique. 3GPP has already started working on the definition of standards such as LAA.

LBT is a version of DCF and contention-based medium access technique similar to the CSMA/CA mechanism used by WiFi [6], meaning that LBT does not allow a cellular node to occupy a channel all time. Instead, LBT shares a channel between a cellular node and a WiFi AP fairly [7] by enabling a cellular node to stop periodically its channel occupancy and to detect the activities of other shared nodes at a millisecond-level [7] following the stepwise procedure given below. Major distinctive features of LBT are that it meets regulatory requirements, as well as it is accepted by both cellular nodes and WiFi APs, because of its CSMA/CA-like operations [6]. 3GPP adopts LBT for LAA and NR-U technologies [71].

- Step 1: *Check the activity of a channel*: A cellular node first listens to the channel to detect the energy level for a period termed CCA. The ED threshold E_T is defined by the regional regulatory requirements [38].
- Step 2*: Compare the detected energy*: The cellular node then compares the energy level detected E_d with that of the threshold energy level. If $E_D \geq E_T$, the cellular node assumes that the channel is busy. Else if $E_D < E_T$, the cellular node starts using the channel for a fixed time period, termed as COT.
- Step 3: *Recheck the activity of a channel*: Followed by COT, an idle period T_I such that the CCA spans over the end duration of T_I is then considered, and the node rechecks the channel activity to detect again the energy level during the CCA.
- Step 4: Keep repeating Steps 1 through 3 until the end of transmission of the cellular node.

Note that T_I should be at least 5% of COT [7], whereas, E_T is adaptive, particularly, in the downlink [64]. The European Telecommunications Standards Institute (ETSI) *frame structure* of LBT is shown in Fig.2 [72]. The summation of COT and T_I defines the period of a frame, and hence the above procedure is termed as *frame-based LBT.*

Another type of LBT is termed *load-based LBT*, which does not require following a fixed transmit/receive pattern [16], [73]. It is rather asynchronous and driven by demand [73-74]. Once the data is available for transmission, load-based LBT nodes perform the channel access procedure immediately [71]. In doing so, load-based LBT nodes carry out the following steps [71]. Nodes execute a random back-off algorithm with variable contention window size. LBT is performed iteratively for a period of at least N consecutive CCA slots (also termed as the contention window) and N is generated by each node independently from a uniform distribution defined between 0 and a maximum contention window size. This is called the category 4 LBT process [71]. After completing this process, nodes can start the transmission and occupy the channel continuously for a maximum interval of time defined as MCOT [71].

In [75], by Channel Access Priority Classes (CAPCs), numerous configurations of maximum contention window sizes and the durations of MCOT are defined. ETSI mandates that the assertion of CCA can be carried out following the provisions of the IEEE 802.11 standard [76]. Or else, minimum requirements should be met, as defined by channel access options specified in [74]. Load-based LBT is fairer than frame-based LBT when coexisting with other RATs [71], whereas frame-based LBT could be a natural choice for LTE since LTE also has a fixed transmission frame structure [16]. However, the fixed CCA window in the frame-based LBT is inconvenient in competing with the more aggressive load-based LBT seeking opportunities basically all the time [16].

Besides, LBT introduces extra delay due to the contention time overhead leading to inefficient channel usage. Also, if the duration of transmission burst were too long, large packet delay and jitter would be experienced by WiFi APs. In the following, several features of LBT are discussed.

1) LBT design options: LBT can be designed as synchronous, as well as, asynchronous [**77**]. The synchronous LBT is constrained to transmit in predefined fixed timeslots such that, upon identifying a transmission opportunity (i.e., the channel is idle), a synchronous LBT wireless node can send data only at the boundary of the next frame. Hence, it needs to postpone data transmissions until the beginning of a frame) [73]. In contrast, the asynchronous LBT node can deliver data immediately once it has a transmission opportunity [73]. Frame-based LBT differs mainly from load-based LBT by the fact that in the former case, nodes execute the channel access synchronously, whereas in the latter case, nodes perform an asynchronous channel access process [71].

2) Impact of LBT threshold: The CCA threshold varies with two types of CCA techniques, namely, energy-based CCA and preamble-based CCA. In energy-based CCA, the transmitter does not require any knowledge of the signal structure or packet format as it is a non-coherent operation and measures the total received power within the signal bandwidth [14] [78]. If the detected energy E_{D} is increased, it helps protect the smaller area around LTE Evolve Node B (eNB). However, if E_{D} is increased substantially, the performance of LBT becomes ineffective, i.e., LBT does not have any performance gain. In contrast, if E_{D} is decreased, the coverage area is increased, even though the chance for the eNB to transmit at the same time is reduced [58].

Moreover, ED threshold E_{T} has a substantial effect on the throughput performances of both cellular such as LAA and WiFi coexisting systems. In [79], the effect of varying ED thresholds, including -62 dBm, -72 dBm, and -82 dBm) on the throughput of WiFi and LAA is reported. By calculating the ED probability corresponding to the above ED thresholds, including 0.0, 0.5460, and 1.0, it is shown that an increase in the WiFi detection probability while keeping the detection probability of LAA nearly equal to 1, decreases the WiFi throughput. This is because, with a decrease in the WiFi ED threshold (equivalently, an increase in the WiFi detection probability), WiFi nodes can detect LAA nodes at lower transmit power. This causes them to defer their transmission, i.e. enter back-off, resulting in lower WiFi throughput.

However, an increase in the LAA detection probability while keeping the detection probability of WiFi nearly equal to 1, increases the WiFi throughput. This can also be clarified by the similar fact mentioned above that, with a decrease in the LAA ED threshold, LAA nodes can detect more WiFi nodes at lower power, causing them to defer their transmission. This in turn provides WiFi nodes more opportunity to transmit, resulting in increasing their throughput. Likewise, a similar effect of changing the detection probability of WiFi and LTE-LAA on the throughput of LAA in coexistence is shown such that LAA throughput can be increased by increasing WiFi detection probability and decreased by increasing LAA detection probability. The results reported in [79] are in line with those presented in [80].

In the preamble-based CCA, the transmitter declares the channel as busy when the preamble is present and the total received power exceeds a certain threshold value [78]. For example, in IEEE 802.11, when the total received power exceeds -62 dBm and -82 dBm in 20 MHz while using the energy-based CCA threshold and preamble-based CCA threshold, respectively, the channel is declared busy [78]. A preamble appears only at the start of a packet, which is fixed and includes a short training field and a long training field in IEEE 802.11 packets. Usually, preamble-based CCA can be realized by a cross-correlation module, and a high correlation output signifies the arrival of a packet in IEEE 802.11 [14], [78]. Hence, a certain preamble with good autocorrelation or cross-correlation property is necessary for the preamble-based CCA.

Preamble-based CCA takes advantage of higher reliability over energy-based CCA mechanisms. However, it needs to turn its correlation module always on to detect the preamble of a packet. In contrast, since energy-based CCA can be used anytime during a packet, this mechanism could be more suitable for power-saving devices [78]. Because either the energy-based or the preamble-based CCA or both can be used in cellular standards, particularly LAA, the CCA threshold needs to be set carefully based on the scenarios [78].

3) Effect of LBT K parameter: In adjusting the contention window size, when the contention window size CW_p for priority class p reaches the maximum allowable value $CW_{\max}$, WiFi retains this value until collisions occur during retransmissions [81]. If the collision persists even after attempting a certain number of retransmissions while maintaining $CW_{\max}$, the packet is then discarded. Conversely, in LAA-LBT specifications, a K parameter value ranging from 1 to 8 is introduced set by each operator. It defines the number of times $CW_{\max}$ is to be retained in retransmissions. After attempting K retransmissions, LAA-LBT resets CW_{p} to $CW_{\min}$ and retransmission continues from there [82]. The parameter K infect allows LTE-LAA operators to coexist fast in both homogeneous and heterogeneous networks.

More specifically, in [82], it is shown that by setting K=1, an LAA BS can increase its probability of transmission over co-channel neighboring heterogeneous WiFi stations. However, when K is increased such that K=8, the saturation throughput performance of LAA almost matches WiFi to a negligible difference. Likewise, setting K=8 can help prevent the degradation of throughput of co-channel collocated homogeneous BSs. It is noted further in [82] that the initial contention window size has a considerable impact on the performance of LAA, and an optimal contention window size corresponding to the maximum throughput performance can be realized. Moreover, dense LAA networks are affected more by the K parameter. Hence, by detecting the number of co-channel nodes and optimizing the initial contention window size, LAA using the standardized LBT mechanism can achieve significant performance gain.

4) Effect of LBT access priorities: According to the standardized version of LBT as stipulated by ETSI [83], the standard additionally defines four sets of channel access parameters assigned to data packets. Table IV shows the priority class of LBT specified by the ETSI standard with 4 being the highest priority class and 1 is the lowest. Each priority is defined by a prioritization period P0, a range of contention window sizes ($CW_{\min}$ and $CW_{\max}$) or back-off time, as well as a transmission time, i.e. COT [83-84]. COT is the maximum time for a node to utilize the channel. P0 is determined by the packet class and used to determine the channel state (either idle or busy) and differentiate between frame types. Low priority frames wait for longer P0 periods (Table IV). P0, $CW_{\min}$, and $CW_{\max}$ are given in terms of the number of observation slots. These channel access parameters determine the behavior, as well as the duration, of the channel contention. As can be seen in Table IV, packets with the highest priority are more likely to gain access, however, with the shortest duration [83].

TABLE IV
PRIORITY CLASS OF LBT SPECIFIED BY THE ETSI STANDARD [83].

Class	P0	$CW_{\min}$	$CW_{\max}$	COT [ms]
4	1	4	8	2
3	1	8	16	4
2	3	16	64	6^*
1	7	16	1024	6^*

*can extend to 8 ms if a transmission includes 100 µs pauses

In [83], the effect of *priority classes* is reported in terms of effective channel utilization, collision probability, and channel access delay. Effective Channel Utilization (ECU) is defined as the percentage of aggregate time the channel is occupied to successfully transmit packets by any coexisting node. In other words, it shows the extent to which a channel is efficiently utilized without collisions [83]. Under a *one-class* dense deployment scenario, for a typical dense deployment of a future 5G NR-U network in [83], it is shown that ECU significantly declines as the number of contending nodes increases. Classes 3 and 4 exhibit an inferior performance compared to the two lower priority types. The decline in ECU is attributed to collisions on the channel. More specifically, since the contention window sizes of class 3 and class 4 are smaller, they are more susceptible to collisions than the other two priority types.

However, under a multi-class dense deployment scenario, particularly for a two-class scenario with priority differs in one level in [83], it is shown that with an increase in *higher priority* nodes in the channel, the total ECU of both classes priorities drops substantially with an increase in nodes due to the increased collisions on the channel. For example, total ECU for classes 3-4 drops sharper than that for classes 1-2 because of the adverse effect of collisions in both higher priority classes 3 and 4 (Table IV). In short in multiple-class scenarios, the total ECU degradation is associated mainly with higher priority classes on the channel. Moreover, low priority class nodes tolerate longer mean access delays than high priority classes [83]. This is because, due to smaller contention window sizes of high-priority classes, they are more likely to access the channel. This results in yielding little time to access the channel for the transmission of lower priority classes and hence causing them to sustain longer delays than higher classes [83].

5) LBT specification: The LBT was standardized in March 2016. 3GPP recommends the following LBT channel access schemes, i.e., LBT is categorized into four:

- *Category 1 LBT (No LBT)*: In this scheme, no LBT procedure is considered to perform by the transmitting entity. For NR-U, an immediate transmission after a switching gap of 16 µs is considered.
- *LBT without random backoff*: In this scheme, before the transmitting entity transmits, the duration of time that

the channel is sensed to be idle (i.e., CCA period) is deterministic, e.g. 25 μs.

- *LBT with random backoff in a contention window of fixed size*: In this scheme, the transmitting entity draws a random number *N* within a contention window the size of which is fixed and specified by the maximum and minimum value of *N*. The value of *N* determines the sensing time duration of the channel to be idle before transmitting on the channel by the transmitting entity.
- *LBT with random backoff in a contention window of variable size*: In this scheme, the transmitting entity draws a random number *N* within a contention window the size of which is specified by the maximum and minimum value of *N*. The size of the contention window can be varied by the transmitting entity. The value of *N* determines the sensing time duration of the channel to be idle before transmitting on the channel by the transmitting entity.

Note that the LBT coexistence mechanism is not mandatory to apply in all regions and standards. For example, in Europe and Japan, LBT is a mandatory feature when operating in the 5 GHz and 60 GHz bands, whereas, in the USA and China, LBT is not required during the early commercialization of LTE [13]. Similarly, standards such as LTE-U do not employ LBT, whereas, LAA standard requires LBT to meet regional regulations. Moreover, if any standard is not LBT enabled such as LTE-U, cellular nodes cannot sense the channel activity, resulting in suffering to access the shared channel by WiFi nodes. Hence, in such cases, a new coexistence mechanism is needed to allow WiFi nodes to get access to the shared channel, which we discuss in the following approach 2.

B. Approach 2: Cellular Networks without Employing the LBT Mechanism

This approach is applicable to regions where there are no obligatory QoS requirements. Interference due to the coexistence can also be avoided in time, frequency, and power, domains in regions where the enforcement of LBT is not required. In frequency and time domains, the principle of coexistence is based on maintaining the orthogonal transmission of each coexisting node in frequency and time, respectively [35-37]. In other words, only one node, i.e. either a WiFi AP or a cellular node, can transmit at a time to avoid collision as follows.

1) Frequency-domain: In general, numerous blocks of spectrum bands are available in the unlicensed bands, e.g. in the 5 GHz band (5.35-5.47 GHz and 5.85-5.925 GHz). However, a WiFi AP typically accesses one channel at a time such that there is a high possibility that a few channels are left unused, and can be used for the transmission of a cellular node [6]. If in case any clear channel is not available, a cellular node can measure the interference level on each channel, and unlicensed data can be transmitted over the channel with the least level of interference [38]. In this regard, interference levels can be measured by technologies such as ED. Hence, the *CHS Mechanism* given as follows can be used as a frequency-domain coexistence mechanism to ensure that a cellular node is a good neighbor when operating in an unlicensed band just by chasing the cleanest channel [85].

In the CHS mechanism, a cellular node (e.g., LTE-U) monitors to classify different channels in the unlicensed band based on their potential (e.g., whether or not a channel is identified as a clear channel) for cellular operations to find the best channel for the *Supplemental Downlink (SDL)* transmission (supplement to the licensed spectrum's transmission). If a clear channel C_1 is identified, the secondary cell can be operated without taking into account co-channel communications [85-86]. Moreover, if in the operating channel C_1, interference is found, and another clearer channel C_2 is available, the transmission can be switched to the new channel C_2 from C_1 [85]. However, if no clear channel is identified (by measuring the channel energy level), the CSAT mechanism can be used [64], [86].

An example CHS mechanism for a cellular SC is shown in Fig.3 for channel 1 only. As it can be shown that channel 1 is selected by the SC only when channel 1 is either clear or with the lowest interference level by moving into it from another channel. Likewise, if channel 1 is sensed with the highest interference level, the SC then moves out of channel 1 to another channel. The above explanation is applicable for all other channels in Fig.3. This mechanism is well suited for low traffic density as it corresponds to a high probability for the existence of a clear channel [64].

For most cases, the CHS mechanism is sufficient for the coexistence of a cellular node with a WiFi AP as long as the traffic density is low [14], [85]. However, in areas such as dense deployments where no clear channel is available, a further process called Opportunistic Supplemental Downlink (OSDL) is required to address the co-channel communications [14]. In this mechanism, the secondary cell on the SDL carrier in the unlicensed band can be used opportunistically such that the SDL carrier can be turned off if the secondary cell is lightly loaded to avoid transmitting control signaling overheads (e.g., cell-specific reference signals) in order to reduce channel interference to the neighboring WiFi APs [3], [38], [64], [86]. When the traffic is increased substantially [86], even though no clear channel is available, the secondary cell can be turned on by invoking CSAT operation, i.e. the secondary cell (cellular node) operates for a certain duration of time of x msec and the WiFi AP operates for y msec, periodically. The value of x and y can be made adaptive based on the channel utilization by the cellular node and the WiFi AP over the duty cycle of (x+y) msec [3], described in what follows.

2) Time-domain: In the time-domain, using the modified versions of the Almost Blank Subframe (ABS) based Enhanced Intercell Interference Coordination (eICIC) techniques [87-88] proposed for LTE-Advanced systems, the transmission of a channel can be switched on and off periodically such that during on time, cellular nodes can transmit, while WiFi can be scheduled during the off-time. CSAT [89], FBS allocation, WiFi white space exploitation, and neural networks technology are representative techniques to provide time-domain coexistence [89-90] discussed in the following.

a) CSAT: The main principle of CSAT is that time is divided into Time-Division Multiplexing (TDM) cycles, termed as CSAT cycle, as shown in Fig.4. Each Cycle consists of an on-period and an off-period. As shown in Fig.4, cellular nodes operate during the on-state, whereas WiFi APs operate during the off-period. Based on the utilization of the channel by WiFi APs, the ratio of T_{ON} to T_{OFF} is updated dynamically. Moreover, to avoid unnecessary delay to support delay-sensitive data and control packets in WiFi, small and frequent gaps are introduced (i.e., T_{ON} is punctured such that some subframes are completely muted during which WiFi can access the channel to transmit delay-sensitive control packets) as shown in Fig.4. Typically, one punctured subframe in every 10s of milliseconds is needed. The duration of the CSAT cycle is not fixed, rather varies with the solutions. For example, according to [86], the length of the CSAT cycle should be greater than 200 ms to measure the channel condition at least once. However, according to the LTE-U forum, the maximum length of the CSAT cycle is 50 ms [91]. In general, a longer CSAT cycle results in higher capacity due to less overhead in carrier activation, whereas a shorter CSAT cycle results in a reduction in latency impact to delay-sensitive traffic on WiFi [92].

CSAT benefits from ensuring fair and efficient channel sharing between cellular nodes such as LAA nodes, and WiFi APs. Moreover, the CSAT mechanism does not require any changes to the underlying RAT communication protocol [38], [86]. Furthermore, it is an attractive candidate for those operators who need to increase their capacity in a short span. However, CSAT also suffers from its long latency as compared to that of CSMA [14]. Moreover, in duty cycling, the degree of fairness is controlled by the cellular nodes such that WiFi APs can just adapt to the rules set by cellular nodes. Hence, WiFi APs are controlled by cellular nodes, which may lead to poor performances of WiFi APs [14].

b) Fully Blank Subframe: Fully Blank Subframes (FBSs) offer more flexibility than CSAT. Using the ABS-based eICIC techniques, ABSs can be modified such that no control signaling is transferred during ABSs. The resulting ABSs are then termed FBSs [93]. Cellular nodes can be allocated to only non-blank subframes, whereas IEEE 802.11 nodes can be allocated to blank subframes to serve their respective data traffic on the same spectrum band. Blank subframes can be distributed optimally over the frame or like ABS-based eICIC, over the FBS Pattern Period (FPP) set by the cellular operator to ensure QoS to WiFi nodes without compromising the performance of cellular nodes [94]. The degree of fairness between cellular and IEEE 802.11 nodes can be updated by changing the number of blank subframes over a certain period (i.e., the duration of a frame or an FPP) as shown in Fig.5.

A major characteristic of bank subframe-based mechanism is that the throughput of cellular nodes decreases (equivalently, the throughput of WiFi nodes increases) with an increase in the number of blank subframes. Moreover, because WiFi transmissions cannot be confined completely within the blank subframes, the interference and hence the throughput degradation increases with an increase in the number of instances that the blank subframes are nonadjacent. However, by informing the duration and occurrence of blank subframes during the negotiation phase to WiFi nodes, it may be possible to confine their transmissions within blank subframes to avoid interference with cellular nodes [14].

c) WiFi white space exploitation: Even though CSAT and ABS (or FBS) can improve the LTE-U and WiFi coexistence by providing a fair throughput balance, they are unable to reflect the disturbance and the resulting latency experienced by the WiFi due to the LTE-U interruption [95]. Since in practice, the WiFi traffic is bursty, it results in a huge amount of *white spaces* between frames as shown in Fig.6. White spaces are vacant portions containing nothing but white noise [96]. The existence of such white spaces creates a huge source of spectrum in the unlicensed bands for cellular technologies such as LTE-U [97] that can access them opportunistically without interfering with WiFi activities. Hence, LTE-U can exploit these white spaces to transmit opportunistically. Since WiFi generates random and bursty traffic, WiFi white spaces and hence the LTE-U duty cycle varies over time. In this regard, Markov Modulated Batch Poisson Process (MMBPP) Model [97] and Reinforcement Learning Technique [95] are example approaches that can exploit WiFi white spaces to provide an opportunistic coexistence mechanism between LTE-U and WiFi discussed in the following.

- Markov Modulated Batch Poisson Process Model

In [97], an opportunistic coexistence mechanism is presented that allows an LTE-U BS to estimate dynamically the duration of WiFi white spaces using Markov processes with group Poisson arrivals, or specifically, a Markov Modulated Batch Poisson Process (MMBPP) framework. MMBPP captures the states and dynamics of the WiFi network, as well as the batch packet arrivals and bursts of WiFi traffic, along with characterizing the distribution of white spaces statistically. Further, MMBPP is suitable to model self-similar traffic arrivals and dependent inter-arrival times, as well as correlated batch sizes [99], due to its diverse adaptability and analytical tractability [100]. It works as follows.

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The LTE-U BS continues to monitor the activity of WiFi in the channel (determined by the cumulative traffic from all WiFi APs in the coexisting WiFi network [99]) by sensing the carrier to know the arrival instances of WiFi frames. When the channel is sensed idle, LTE-U BS understands that there is a white space. The BS then starts transmitting over the channel for the estimated duration of the white space subject to the duration longer than 1 ms and stops transmissions by the end of the estimated white space duration to make the channel available for the next WiFi frame arrival. If the estimated duration is shorter than the minimum requirement, LTE-U does not transmit and waits for the next one fulfilling the minimum requirement.

Although the MMBPP-based approach can obtain similar throughput to ABS (or FBS) and reduce the latency encountered by WiFi considerably, MMBPP is practically difficult to implement, due to the parameter estimation and computational complexities. Moreover, because LTE-U probabilistic operation is subject to error, it may cause variation of the WiFi system statistics, which, however, is not captured in the model [95].

- Reinforcement learning technique

To address the above issues with MMBPP, the problem of opportunistic coexistence of LTE-U and WiFi can be performed by a reinforcement learning technique. For example, in [95], an approach based on reinforcement learning, particularly Q-Learning, is proposed, which provides a robust and model-free decision-making framework that enables the online and distributive coexistence of LTE-U SCs with WiFi.

The LTE-U BSs are reinforcement learning agents that can autonomously schedule transmissions taking into account the coexisting WiFi network activity. The LTE-U BS detects WiFi activities in the unlicensed band by employing the carrier sensing mechanism. LTE-U listens to the unlicensed channel about the WiFi activity and starts transmitting over the channel when it detects a white space for $t_{\text{on},b} = \left(b \times t_{\text{LS}}\right)$ where $b \in \{b_1, b_2, ..., b_n\}$ is the integer representing the number of LTE subframes each equal to $t_{\text{LS}} = 1\,\text{ms}$. To find the best value of b and the corresponding $t_{\text{on},b}$ for LTE-U dynamically, LTE-U BS uses the Q-learning technique where the learning agent improves its behavior through interaction with the environment by estimating the values of state-action pairs based on experience [95].

The learning agent maintains a Q-table where each entry corresponds to a pair of state-action with a Q-value. The Q-value is defined to be the expected discounted sum of future payoffs attained by taking action b in the state s that minimizes the cumulative cost function. A cost function is defined as the absolute difference or error in the prediction of white space duration. More specifically, Let w_t and b_t denote, respectively, the duration of the actual WiFi white space and the length of the ON period chosen as action by the agent (e.g., the BS) at any step *t*. Assuming that the agent can fully observe w_t by sensing WiFi broadcast control signalings such as RTS/CTS, the immediate cost received by the agent from the environment is then defined as follows [95]:

$$c_t = \left| w_t - b_t \right| \tag{1}$$

The value of b_t , and hence c_t , has a substantial impact on the coexistence performance of a cellular node operating in an unlicensed band. Note that, $b_t > w_t$ results in an additional latency of a WiFi AP due to finding the channel busy by the transmission of the BS. Conversely, $b_t < w_t$ results in underutilization of the unlicensed spectrum (i.e., WiFi white space). Consequently, a small value of c_t results in a maximum unlicensed spectrum utilization by the BS while minimizing WiFi latency. Hence, the goal of the BS is to choose the values of b_t , as close to w_t as possible.

Besides, a state $s_t \in S$ at any cycle (step) t is determined by the error in the white space duration prediction or the cost function c_{t-1} . At each state s_t , the agent chooses the action b_t . After executing the action b_t , the agent receives cost function $c_t = \left| w_t - b_t \right|$ feedback from the environment to learn about the result of the selected action in the current state. The next state $s_{t+1} \in S$ is then determined from the state space $S \in \{s_1, s_2, ..., s_m\}$, which is defined within the range of the smallest and largest tolerable cost values, $c_{\min}$ and $c_{\max}$, respectively, such that m levels for the error in white space duration prediction is presumed, and is given by the following equation [95].

$$s_t = \begin{cases} s_1, & c_{\text{t}} < c_{\min} \\ s_2, & c_{\min} \le c_{\text{t}} \le c_{\min} + \Delta c \\ s_3, & c_{\min} \le c_{\text{t}} \le c_{\min} + 2\Delta c \\ \vdots & \\ s_m, & c_{\text{t}} \ge c_{\max}, \end{cases} \tag{2}$$

After finding the next state, the prior Q-value is then updated. The Q-Learning-based approach enables LTE-U to dynamically identify and exploit WiFi white spaces without requiring complete knowledge of the WiFi system [95]. Further, by adjusting the LTE-U duty cycle in accordance with the WiFi activity, this approach allows the maximal utilization of idle resources for LTE-U, as well as decreases the latency experienced by WiFi traffic. Furthermore, it performs better than the ABS mechanism and is similar to the MMBPP-based approach under lightly loaded conditions in addition to providing means toward the trade-off between LTE-U utilization and WiFi latency.

d) Neural networks technology: Neural Networks Technology (NNT) can also be used to provide a harmonious coexistence mechanism in time-domain for cellular and IEEE 802.11 technologies in the unlicensed spectrum. Along this direction, in [101], A novel mechanism based on neural networks for the coexistence of an LTE-U BS with WiFi APs in the 5 GHz unlicensed spectrum is proposed. A wireless network, including LTE-U nodes and WiFi APs operating in the 5 GHz band is considered. The coexistence problem is modeled as a 2-Dimensions Hopfield Neural Network (2D-HNN) in terms of neuron states. The time-domain is modeled as equal duration time windows, each divided further into equal duration time slots. Each time slot is represented as a neuron in 2D-HNN, which is updated over each time window.

Neurons with state 1 correspond to ON slots to transmit over them by LTE-U, whereas neurons with state 0 correspond to OFF slots to stop the transmission by LTE-U nodes in order to protect, as well as allow, WiFi APs to transmit (Fig.7). In short, by classifying the time slots into ON/OFF slots and allowing their transmissions on different frequency channels, the data rate of the LTE-U network is maximized while protecting WiFi APs to achieve harmonize coexistence. The major advantage of this approach is that with respect to the existing coexistence techniques, the 2D-HNN-based approach can efficiently solve the coexistence problem online, saves computation time, and achieves a harmonious coexistence [101].

3) Power-domain: In the power-domain, the co-channel interference generated due to the co-existence of cellular nodes and WiFi APs in an unlicensed band can be controlled by applying the power control method (i.e., adjusting the output power) to cellular nodes [102-104]. If the transmission power of a cellular node is decreased, the opportunistic transmission power window of a WiFi AP has increased accordingly as shown in Fig.8. This, however, reduces the achievable capacity of the cellular node due to the degradation in the signal-to-interference-plus-noise ratio.

Besides, using LTE uplink power control, a controlled decrease in the transmit power of LTE User Equipments (UEs) causes to decrease the interference experienced by neighboring WiFi APs, which results in creating opportunities for the transmission of WiFi signals due to identifying channels as vacant by WiFi APs. Specifically, LTE uplink power control defines the transmit power of an LTE UE that compensates the path loss, as well as interference, to maintain a target received signal quality at the LTE BS [105]. Since the presence and proximity of WiFi APs can be determined by measuring the interference at the LTE nodes or UEs, LTE UEs measuring high interference are more likely to cause high interference to neighbor WiFi APs. In such cases, uplink transmit power is reduced according to a fractional compensation of the measured interference that corresponds to decreasing the target signal quality, and hence the LTE UE throughput [106]. Hence, a major difference between blank subframes-based and uplink power control-based mechanisms is that the cellular throughput decreases with an increase in the number of blank subframes in the blank subframes-based mechanism, whereas with a decrease in the uplink transmit power in the uplink power control-based mechanism [105]. Table V shows the comparison of these above coexistence mechanisms for cellular and IEEE 802.11 technologies where in the time-domain, basic coexistence mechanisms, including FBS and CSAT, are only considered.

C. Game Theory-based Coexistence Mechanisms

Game Theory (GT) formalism [107] is the study of decision-making. GT is a powerful mathematical tool that analyzes the strategic interactions among multiple decision-makers [108]. By characterizing the channel selection problem as a game, the behaviors and actions of players can be analyzed [69]. The GT-based solutions consider the coexistence problem from a different point of view where LTE-U and WiFi devices have to compete to gain access to the available resources [109]. Though GT works mostly model the coexistence problem as non-cooperative games, interdependence between the two systems is trivial [109]. For example, continuous transmissions of LTE BSs over unlicensed bands may deteriorate WiFi performances due to the large backoff durations from experiencing high interference, whereas reduced transmissions of BSs to favor WiFi performances may affect LTE QoS guarantees. Hence, the cooperation between LTE-U and WiFi is required to satisfy their respective requirements [109], making the GT based solutions can either be based on the competitiveness (i.e., non-cooperative) [69], [110-113] or the cooperation (i.e., cooperative) [68], [70], [114-116] between LTE-U and WiFi technologies.

A GT-based solution involves many agents or players. Each player needs to choose an action that corresponds to either a reward or a sanction [107]. As reported in [109] with regard to the coexistence of LTE-U in an unlicensed band, [69] is one of the early works on the GT paradigm where the problem is modeled using a non-cooperative repeated game. The LTE-U system is modeled as a set S_F of SCs operating in the 5 GHz band and the total bandwidth as W consisting of a set of V channels such that $\boldsymbol{Y} = \{1,...,V\}$. The channel selection problem consists of the decision-making process, carried out by each SC individually. The global process is modeled as a repeated game where each SC participates as a player. At each time step t, a player j performs an action $y_j(t) \in \boldsymbol{Y}$ comprising the selection of a channel for the transmission. After the selection of channels using an algorithm called Iterative Trial and Error Learning-Best Action (ITEL-BA) made by all players, a player j gets a reward $r_j(y_j(t))$ or payoff at the end of t. Evaluating in an indoor scenario under different conditions concerning the number of players and the presence of external influence, the proposed framework has been shown to converge to Nash Equilibrium (defining the optimality of the proposed framework).

Other GT-based works considering the coexistence problem as non-cooperative games include [110-113]. Particularly, in [110] and [113], sharing of the unlicensed spectrum by strategic operators is studied by formulating the spectrum sharing problem as a repeated game over a sequence of time slots. In [111-112], the resource allocation problem with uplink and downlink decoupling is studied for an SC network in LTE-U by formulating the problem as a noncooperative game, which jointly incorporates user association, spectrum allocation, and load balancing. A distributed algorithm based on the machine learning framework of echo state networks is proposed to solve the problem. With simulation results, it is shown that the proposed approach can attain significant gain in terms of the sum-rate while providing a considerable reduction of information exchange.

However, non-cooperative games ignore the dependence between the LTE and WiFi networks. As mentioned earlier, due to the interdependencies, the inter-network interactions may affect the coexistence performances, particularly the channel access performance. Hence, instead of addressing only the competition between them, cellular and IEEE 802.11 technologies may operate in a cooperative mode to serve mutual interests [109]. In line with so, the cooperation between LTE-U and WiFi on the unlicensed bands is addressed numerous studies. Particularly, for the cooperation between LTE-U and WiFi systems in the unlicensed bands, the Device-to-Device (D2D) communication under the LTE standard operating in the unlicensed spectrum bands is investigated in [68] taking into account LTE and D2D users' QoS requirements while protecting minimum requirements of WiFi APs. Solving the problem with the help of the Nash bargaining game between SC BSs and WiFi APs by the cooperative approach, the effectiveness and efficiency of the presented cooperative approach are reported.

Moreover, in [114] and [115], a coexistence mechanism between LTE-U and WiFi systems is studied in a dense deployment scenario in view of multiple SCs from different operators. An LTE-U sum-rate maximization problem is formulated subject to constraints, including the user QoS and the co-existence of WiFi and LTE-U. A cooperative Nash bargaining game allowing LTE-U and WiFi nodes to share time resources while protecting the WiFi system is proposed to solve the problem. A heuristic algorithm is proposed to allocate unlicensed resources among LTE-U users. It is reported that along with protecting WiFi users better than the LBT, the proposed method provides better performances in terms of per-user achieved rate, percentage of unsatisfied users, and fairness than other compared methods. To address a similar problem (i.e., an effective coexistence mechanism between LTE-U and WiFi systems), in [116], a multi-gaming approach is used. Particularly, a cooperative Nash bargaining game to share time resources between LTE-U and WiFi systems, and a bankruptcy game to allocate unlicensed resources among LTE-U users by operators, is used. With simulation results, it is reported as well that the proposed approach is better than the comparing methods in terms of the per-user achieved rate per user and fairness while outperforming LBT in protecting WiFi users in a dense deployment. Moreover, in [70], a multi-game cooperative framework is proposed that can capture the specific characteristics of LTE-U and their interdependence with the WiFi network.

A multi-game G composed of multiple interdependent games $G=\{G_1,...,G_N\}$ each modeling a specific resource management problem at either the WiFi level, or the LTE level, or the coupled level [70]. G can be defined by three parameters, namely, the players, the actions, and the utility function. The players can be LTE BSs, WiFi APs, LTE UEs, or WiFi UEs each associated with a set of actions. Each player chooses its strategy from its set of actions that maximizes a utility function corresponding to its goal in the network. For example, in LTE-U and WiFi coexistence, LTE BSs aim to maximize the quality of experience by their users, whereas WiFi UEs would like to deliver a maximum amount of data. The utility is given by a function $u_m\left(a_{-m},\{\boldsymbol{o}_i\}_{n=1,...,N\backslash n}\right)$ depending on the actions that are selected by all its co-players in the game G_n , as well as the outcome of all the other games denoted as $\boldsymbol{o}_i$ for each game G_i . For example, in LTE-U and WiFi coexistence, the throughput of a WiFi UE is limited by the interference from both LTE BSs and WiFi UEs transmitting over the same channel [70].

However, instead of either competition or cooperation, a combination of both types of games is used in several works such as [117]. In [117], a novel spectrum sharing framework that considers both cooperation and competition, (also termed as coopetition) between LTE and WiFi in the unlicensed band is proposed. The LTE network can select one of the two modes, either competition mode or cooperation mode. In the competition mode, an LTE node randomly accesses an unlicensed channel and hence interferes with the WiFi node when using the same channel. In contrast, in the cooperation mode, an LTE node onloads traffic of WiFi users in exchange for occupying exclusively the corresponding channel. Since no transmission is made by WiFi nodes during onloading their traffic, it results in achieving a high LTE data rate due to avoiding co-channel interference. Also, since the spectral efficiency of LTE is usually much higher than WiFi [118], cooperation between them leads to a win-win situation for both LTE and WiFi networks. Cooperation is especially important under certain conditions, including if the data rates of both LTE and WiFi are reduced considerably due to co-channel interference, it would be beneficial for both LTE and WiFi to cooperate with each other. Hence, to sum up, the basic idea here is that both LTE and WiFi should explore the possible benefits of cooperation before deciding whether to enter a competition [117].

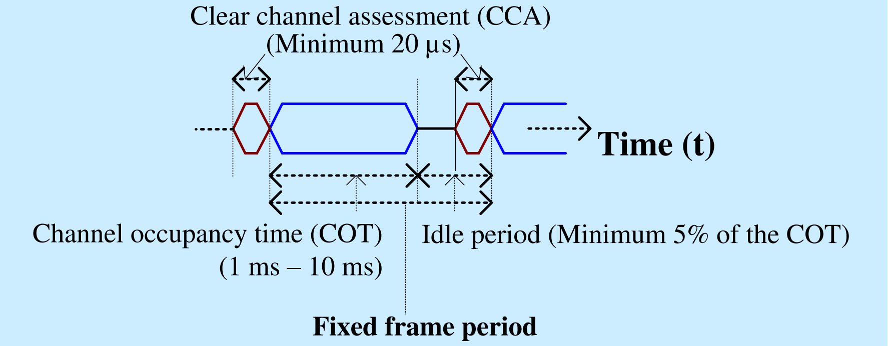

Fig.2. ETSI LBT frame structure [72].

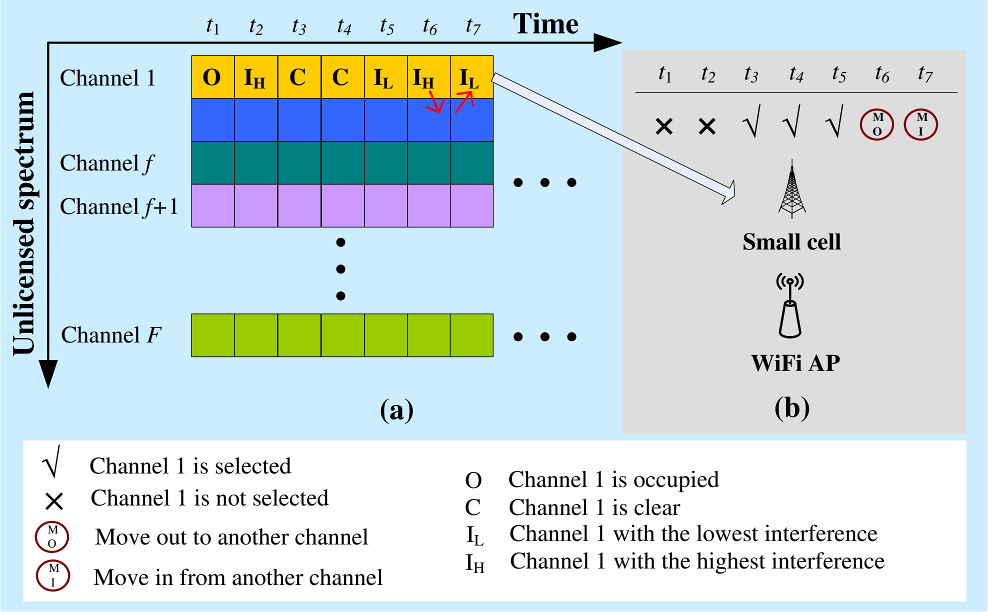

Fig.3. An illustrative channel selection mechanism for a cellular SC coexisting with a WiFi AP.

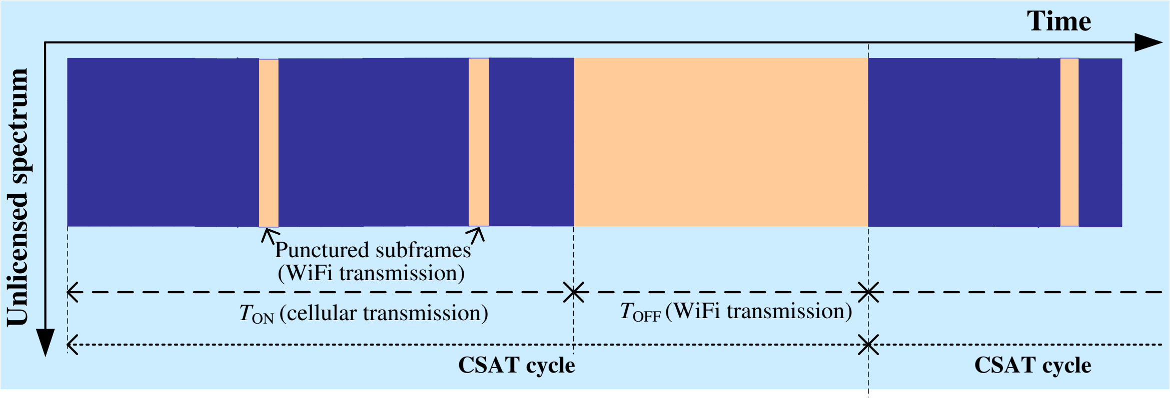

Fig.4. CSAT cycles and punctured subframes in the CSAT mechanism.

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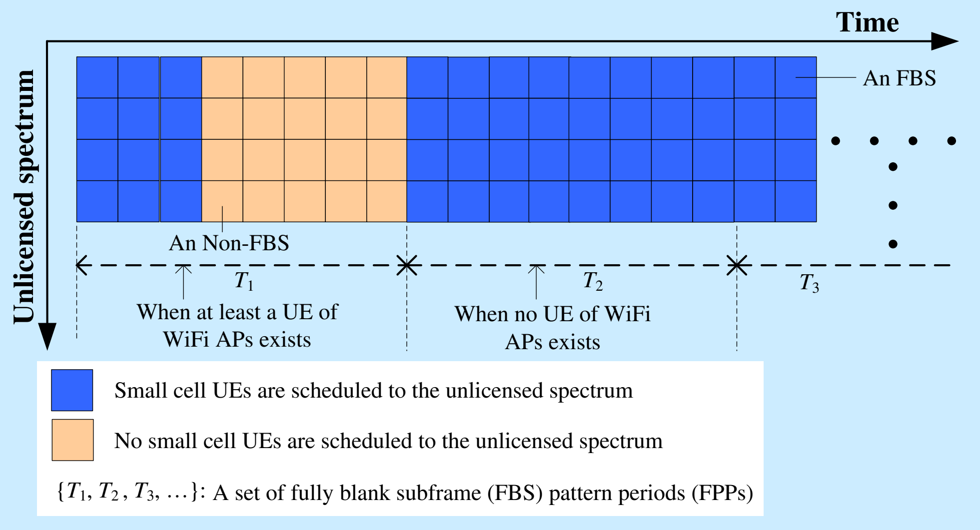

Fig.5. An illustrative FBS allocation to cellular SCs over an FPP.

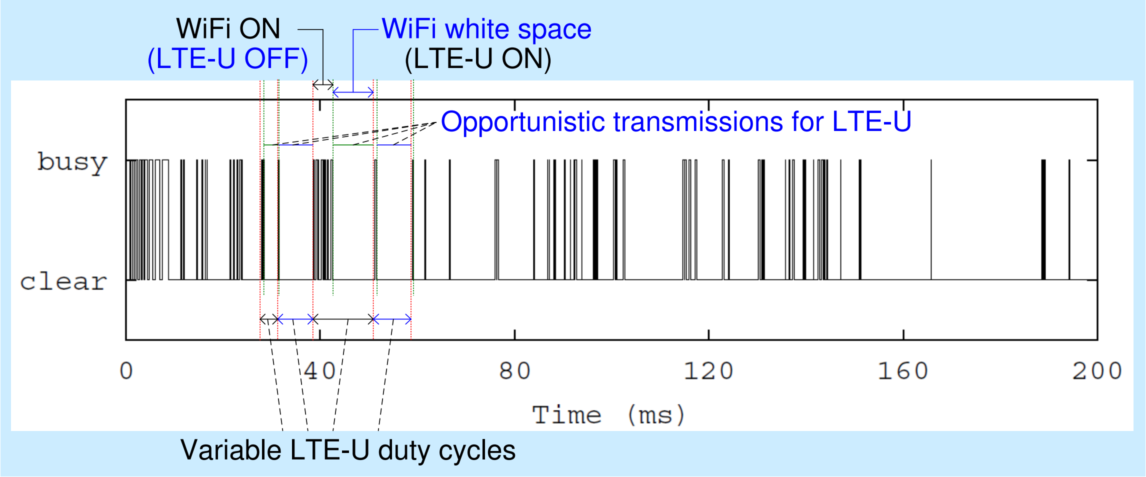

Fig.6. Bursty and random channel state trace of a real-life WiFi network [95], [98]. An LTE-U can transmit during white spaces, i.e. no WiFi channel traffic.

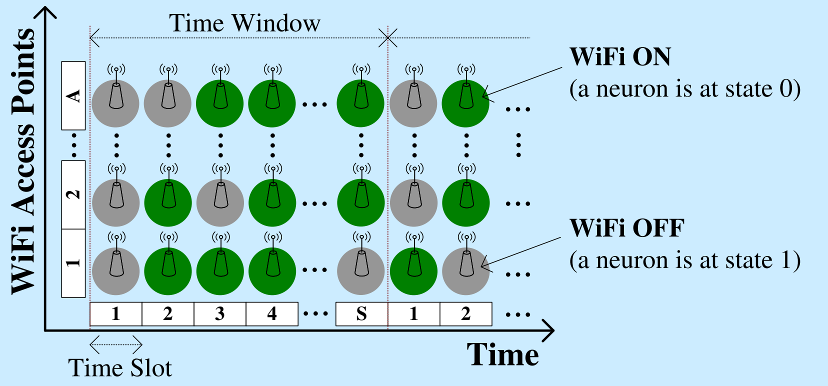

Fig.7. 2D-HNN-based LTE-U/WiFi coexistence mechanism proposed by [101]. Here, WiFi APs are shown in the y-axis, and time slots (each representing a neuron) are shown in the x-axis. Based on the states of a neuron (either 1 or 0), a WiFi AP is allowed to transmit. Each ash color WiFi AP represents that a neuron is fired (i.e., at state 1), which implies that the WiFi AP is not allowed to the time slot corresponding to the neuron fired. Likewise, a green color WiFi AP is allowed to transmit on the corresponding time slot.

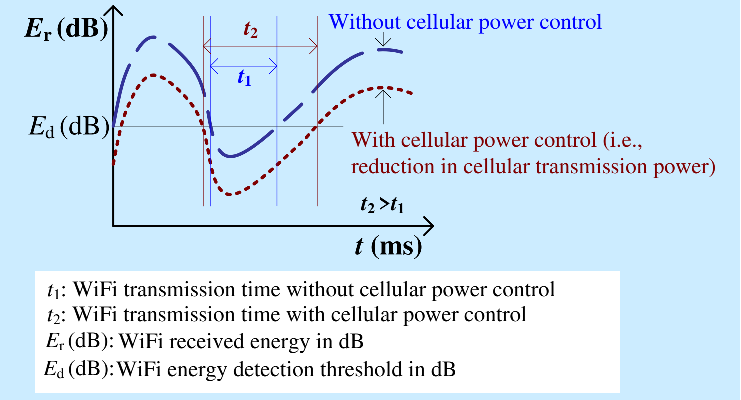

Fig. 8. An illustration of dynamic channel access of WiFi APs with/without cellular power control (i.e., reduction in cellular transmission power).

TABLE V
COMPARISON OF COEXISTENCE MECHANISMS FOR CELLULAR AND IEEE 802.11 TECHNOLOGIES.

Aspect	**LBT**	**FBS**	**CSAT**	**CHS**	**TPC**
Domain	Time	Time	Time	Frequency	Power
Design	Four design options: • No LBT • LBT without random backoff • LBT with random backoff in a contention window of fixed size • LBT with random backoff in a contention window of variable size	Allocation of channel time to each competing entity [14]	Defining a TDM cycle for the transmission of a cellular node [14]	Channel scanning to classify different channels given their conditions [14]	UL power control is based on an interference-aware power operating point [14]
Channel occupancy	based on the channel access priority class [119] and opportunistic [6]	Deterministic and periodic [6]	Deterministic and periodic [6]	Random and opportunistic	Random and opportunistic
MAC [6]	Contention-based transmission	TDM based transmission	TDM based transmission	ED-based transmission	Interference measurement based transmission
Scheduling	Distributed (similar to CSMA/CA)	Centralized (by cellular BSs)	Centralized (by cellular BSs)	Distributed (user-assisted measurement based)	Centralized (by cellular BSs)
Regulatory requirements fulfilled [6]	All regions of the world	Only specific countries such as the USA, China	Only specific countries such as the USA, China	All regions of the world	All regions of the world
Acceptance by WiFi and LTE communities [6]	Both	Only LTE	Only LTE	Only LTE	Only LTE
Operational time scale [6]	1 ms to 10 ms	10 ms to 100 ms	10 ms to 100 ms	100 ms to 10 s	10 ms to 100 ms
Adaptation [6]	Carrier sensing-based	Carrier sensing-based	Carrier sensing-based	User-assisted measurement-based	Interference measurement-based
Fairness in channel access	Fairer	Less fair as controlled by cellular nodes	Less fair as controlled by cellular nodes	More fair than CSAT given that clear channels are available	Less fair as controlled by cellular nodes
Pros [6]	Meet global regulations	No impact on air interface protocol	No impact on air interface protocol	No interference to WiFi given that clear channels are available	No impact on air interface protocol and meet global regulations
Cons [6]	Potentially lower spectral efficiency	Potentially higher probability of packet collision than CSAT[6]	Potentially high probability of packet collision at the beginning of LTE ON period [6]	Subject to the availability of clear channels	Normally used together with other coexistence mechanisms

V. COEXISTENCE DEPLOYMENT SCENARIOS AND STANDARDIZATION EFFORTS

Due to the variation in supported enabling technologies of one cellular standard from the other, including CA, Dual Connectivity (DC), and standalone operation, coexistence deployment scenarios vary with the cellular standard. Moreover, standardization bodies such as 3GPP and IEEE are addressing a number of coexistence issues, including supported unlicensed bands and coexistence mechanisms, between cellular and IEEE 802.11 standards. In the following, we discuss deployment scenarios and standardization efforts of LTE-U, LAA, and NR-U cellular standards when coexisting with IEEE 802.11 standards in unlicensed bands.

A. Coexistence Deployment Scenarios for LTE-U

LTE-U operates in two modes, namely SDL and Time-Division Duplex (TDD). SDL is a simple form of LTE-U, which is used only for the downlink transmission. Because of heavier traffic demand in the downlink, SDL is used for data-hungry applications such as video steaming [7]. However, in TDD mode, the unlicensed spectrum is used for both the uplink and downlink transmissions. It offers flexibility to adjust uplink and downlink resource allocations at an additional complexity on the UE side. It is typically used for those applications that need high uplink data rates such as real-time video chatting. Since unlicensed bands are transmit-power limited, LTE-U is suitable for a small area [7]. Moreover, LTE-U can aggregate with the licensed band of LTE using the CA technology such that LTE-U deployments in Heterogeneous Networks (HetNets) can be categorized into three scenarios as follows [120], which are illustrated in Fig.9.

- Non-collocated scenario
- Collocated scenarios
- Standalone scenario

In Fig.9, the licensed band operating at the macrocell and the unlicensed band operating at the SCs are aggregated at the CA-enabled UE. In the *non-collocated scenario* shown in Fig.9(a), licensed and unlicensed bands are deployed in separate cells, which are aggregated together using the CA technology. For coordination, ideal or non-ideal backhauls may be used between aggregated cells. In the *collocated scenario* shown in Fig.9(b), both the licensed and unlicensed bands are deployed at the same SC, which is then aggregated using the CA at the UE within an SC coverage. In a *standalone scenario*, SCs are operated only at an unlicensed band as shown in Fig.9(c), which is suitable for indoors, as well as outdoor hotspots.

B. Coexistence Deployment Scenarios for LAA

In general, considering an appropriate deployment scenario depends on an operator's strategy as well as the availability of the type of backhaul. 3GPP designed four deployment scenarios for the SCs in LAA [121] as shown in Fig.10, if there exist ideal backhauls between the macrocell and SCs.

- Scenario 1: CA between a licensed macrocell (F1) and an unlicensed SC (F3).
- Scenario 2: CA between a licensed SC (F2) and an unlicensed SC (F3) without the macrocell coverage.
- Scenario 3: Licensed macrocell and SC (F1) with CA between the licensed SC (F1) and an unlicensed SC (F3).
- Scenario 4: CA between the licensed macrocell (F1), licensed SC (F2), and unlicensed SC (F3).

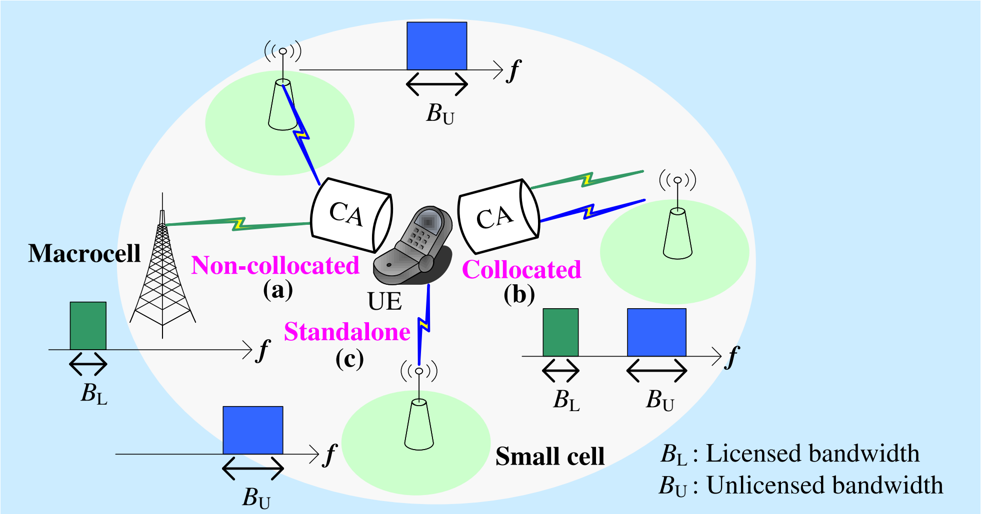

Fig.9. LTE-U deployment scenarios. (a) non-collocated scenario, (b) collocated scenario, and (c) standalone scenario [120].

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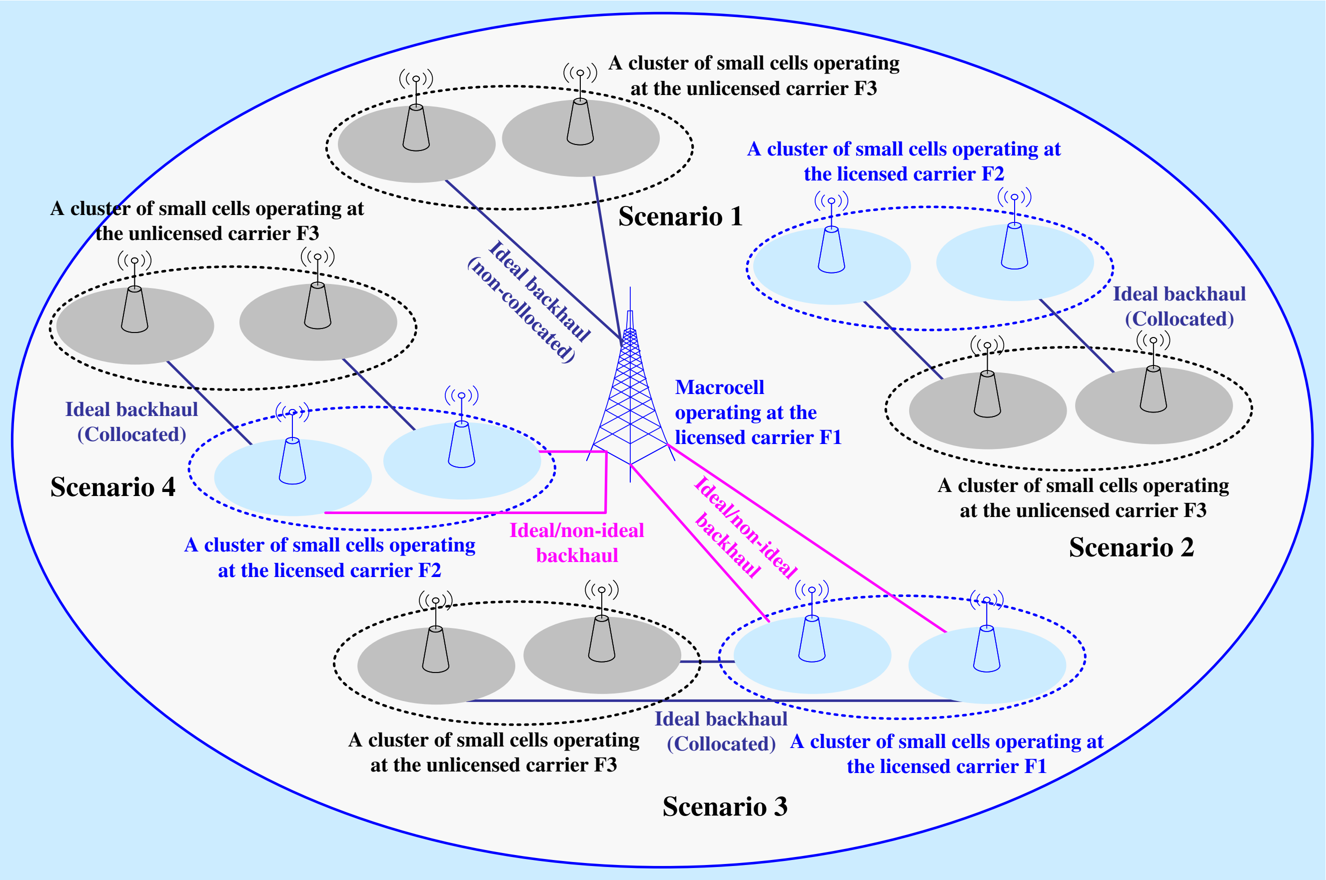

Fig.10. LAA deployment scenarios considered by 3GPP [121].

All these above scenarios are illustrated in Fig.10. As can be seen from Fig.10, in scenario 1, the licensed spectrum F1 is used by the primary macrocell, whereas SCs operate in the unlicensed band F3. SCs are not collocated but linked by the ideal backhaul. In scenarios 2, 3, and 4, the LTE unlicensed SC is always collocated with a licensed SC using an ideal backhaul. Moreover, either the SC (scenario 2) or the macrocell (scenarios 3 and 4) can act as a primary carrier. Furthermore, the licensed SC can operate at either the same spectrum (F1) as that of the macrocell (scenario 3) or a different spectrum (F2) from that of the macrocell (scenario 4). Note that scenario 2 is typically well suited for indoor environments [14].

C. *Coexistence Deployment Scenarios for NR-U*

While LTE-U and LAA operate in the 5 GHz band, NR-U operates in multiple unlicensed bands, namely sub-7 GHz (including 2.4 GHz, 3.5 GHz, 5 GHz, and 6 GHz) and mmWave (37 GHz and 60 GHz). Depending on either the DC or the CA or both DC and CA, considered to communicate over unlicensed bands with UEs, five deployment scenarios are defined by 3GPP *for NR-U* [11] [39] as follows.

- Scenario 1: CA between a licensed band NR and an unlicensed band NR-U where a UE is served through a licensed band by an NR cell and an unlicensed band by an NR-U cell using the CA.
- Scenario 2: DC between a licensed band LTE and an unlicensed band NR-U where a UE is served through a licensed band by an LTE cell and an unlicensed band by an NR-U cell using the DC.
- Scenario 3: Standalone unlicensed band NR-U where a UE is served through one or more unlicensed band(s) by an NR-U cell.
- Scenario 4: NR with downlink in the unlicensed band and uplink in the licensed band where a UE is served through a licensed band for the uplink communication by an NR cell and an unlicensed band for the downlink communication by an NR-U cell.
- Scenario 5: DC between a licensed band NR and an unlicensed band NR-U where a UE is served through a licensed band by an NR cell and an unlicensed band by an NR-U cell using DC.

All these above scenarios are illustrated in Fig.11. As can be seen from Fig.11, DC and CA modes play major roles in connecting UEs over unlicensed bands. In DC, data of a UE can be exchanged simultaneously with more than one Next Generation NodeBs (gNBs)/eNBs [11]. Note that in multiple gNBs/eNBs, one of them is considered primary

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gNB/eNB while the others as secondary gNBs/eNBs, which are connected with the core network. However, in the CA, data of a UE can be exchanged simultaneously with a gNB/eNB through multiple contiguous or noncontiguous bands [11]. While the CA can help improve the throughput, the DC can improve throughput, as well as reliability. Moreover, in the DC, failure of the primary link does not impact the secondary links [11].

Note that CA in scenario 1 follows the approach of LTE-LAA technologies, whereas the standalone scenario resembles the MultiFire approach [14]. Moreover, the standalone NR-U deployment is complicated due to using the unlicensed band by all signals, which results in affecting initial access and scheduling procedures. Besides, the performance metrics for NR-U coexistence are the same as in LAA [122].

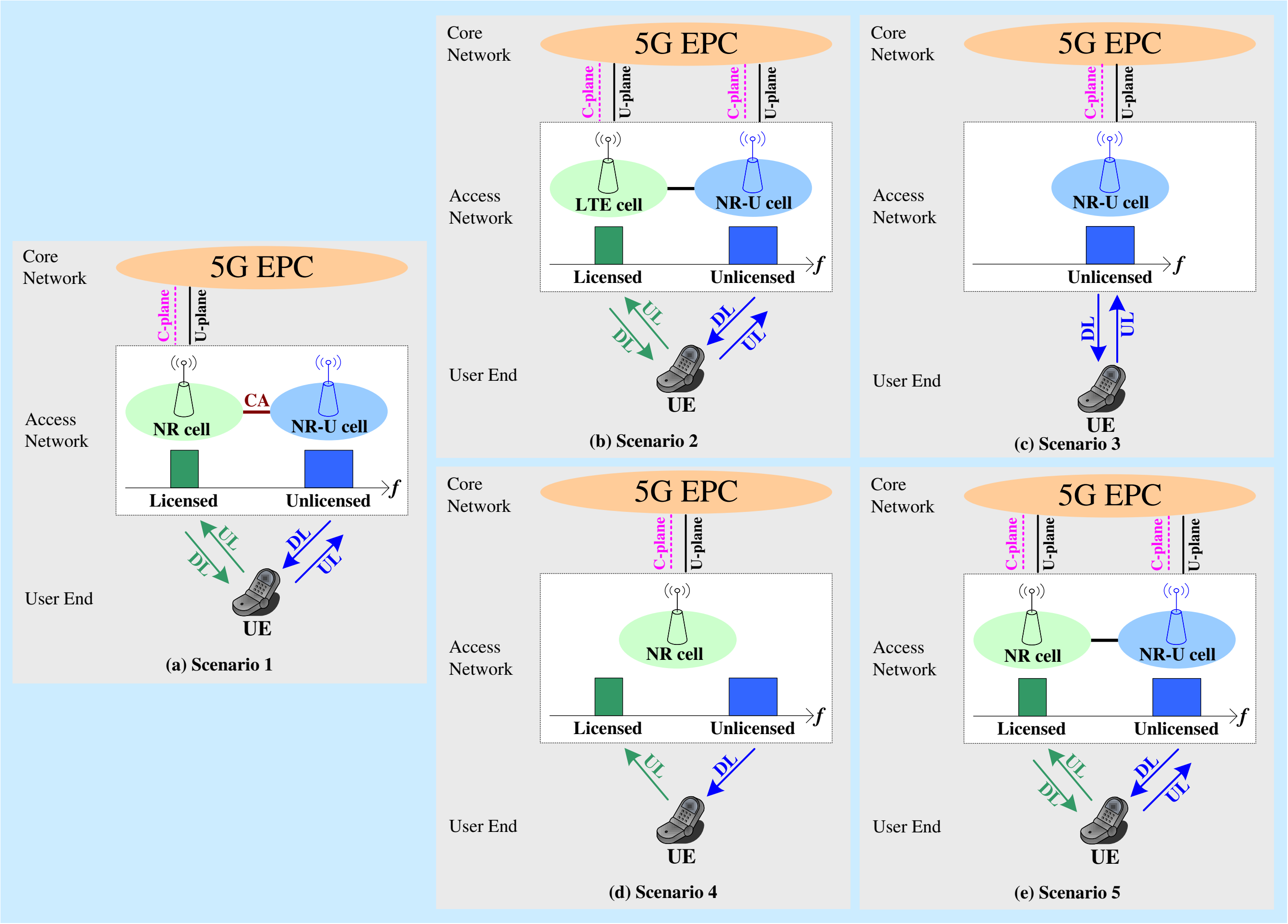

Fig. 11. NR-U deployment scenarios. (a) Scenario 1: NR/NR-U LAA; (b) Scenario 2: LTE/NR-U DC; (c) Scenario 3: NR-U Standalone; (d) Scenario 4: NR/NR-U UL/DL; (e) Scenario 5: NR/NR-U DC. U-plane defines User Plane; C-plane defines Control Plane; UL defines Uplink; DL defines Downlink; EPC defines Evolved Packet Core [11], [13].

D. Standardization Efforts toward Coexistence

The operation of cellular networks has started to expand to the unlicensed bands since the LTE standard in Release 13 [7], [84]. Industry standardization efforts for cellular standards, namely LTE-U, LAA, and NR-U, are discussed in this section. Numerous coexistence issues between cellular and IEEE 802.11 standards, addressed by the standardization bodies such as 3GPP and IEEE, are given as follows.

1) IEEE 802.11: Standardized mechanisms for the IEEE 802.11 standard, commonly referred to as WiFi [3], have been carried out by IEEE to ensure efficient coexistence with LTE networks. An example IEEE initiative is the IEEE 802.11af standard that addresses the operation of WiFi in the Very High Frequency (VHF) and Ultra High Frequency (UHF) bands between 54 and 790 MHz [105]. With the growing demand for WiFi offloading in cellular networks, IEEE 802 Working Group (WG) created IEEE 802.11 High-Efficiency WLAN (Wireless Local Area Network) (HEW) Study Group (SG) in May 2013 [123] to enhance the

Quality-of-Experience (QoE) in dense wireless environments.

Following HEW SG, IEEE 802.11ax Task Group (TGax) was established to further increase user throughput in dense heterogeneous networks (hetnets) [105]. WiFi has expanded rapidly in the 5 GHz unlicensed band. Currently, 802.11a, 802.11n, and 802.11ac devices operate in the 5 GHz band [3]. Moreover, 802.11ax is being developed to operate in the 5 GHz band [3]. Note that existing 802.11 standards use CSMA/CA to avoid collisions, which shows poor performance in dense deployment scenarios [124]. In this regard, the 802.11ax standard plans to overcome this problem with CSMA/CA by introducing protocols, considerably similar to cellular standards to schedule WiFi transmissions [3].

2) 3GPP Cellular: LTE-U is the first LTE standard proposed for operating cellular standards in the unlicensed band [38]. LTE-U is compatible with 3GPP Release 10/11 without requiring any changes in the LTE specifications. It incorporates the CA mode and allows the downlink transmission in the UNII unlicensed band. LTE-U uses channel selection and CSAT coexistence mechanisms. Channel selection is used to find clear channels, whereas CSAT is used when more than one different standards share the same channel [6]. Note that LTE uses unlicensed bands to serve traffic only when its licensed spectrum is not sufficient enough to serve the required traffic demand. Moreover, if no clear channel in the unlicensed band is available, CSAT is used.

LAA is formalized by 3GPP in Release 13. Unlike LTE-U, LAA uses LBT to address regulatory requirements set by different regions in the world. LAA also includes several key functions [121] such as the maximum duration for transmission, downlink-only transmission, dynamic channel, as well as frequency selection, TPC, LBT, and synchronization. The operation of LTE and its variants, including LTE-U in Release 12 [7] and LAA in Releases 13, 14, and 15 [33-34], [79], [125-126], has been focused on the 5 GHz unlicensed band. NR, specified first in Release 15, is being designed by 3GPP with a native feature to operate in the unlicensed spectrum bands through the so-called NR-U [13], [39], [127] in Release 16. The NR standard differs from previous cellular standards by the fact of its inherent support for the operation in the mmWave bands of up to 52.6 GHz.

Unlike LTE-U and LAA, NR-U supports multiple unlicensed bands, including sub-7 GHz (i.e., 2.4 GHz, 5 GHz, and 6 GHz) and mmWave (i.e., 60 GHz) bands. Moreover, in addition to the CA, NR-U supports additional deployment scenarios such as DC and standalone operations in the unlicensed bands. Since other standards such as WiFi (IEEE 802.11a/n/ac/ax) in the 5 GHz and WiGig (IEEE 802.11ad/ay) in the 60 GHz have already been in operation, a fair and efficient mechanism to coexist cellular standards with these above IEEE 802.11 standards subject to fulfilling regional requirements worldwide is necessary. In this regard, 3GPP has specified four LBT categories for the coexistence of NR-U [39], described in an earlier section. Unlike LTE-U, LAA also adopts the LBT mechanism for the coexistence with WiFi, particularly, in regions such as Europe and Japan where the LBT requirement has been mandated for cellular standards to operate in the unlicensed bands.

Recently, FCC approved the 6 GHz band in the USA for spectrum sharing [128]. Likewise, Europe is considering allowing 6 GHz bands to use [20]. In line with so, 3GPP has recently released the specifications for NR-U in Release 16 where the provision for NR-U devices to operate in the 6 GHz band is incorporated [13], [39]. Moreover, IEEE 802.11 WG is actively working in the 6 GHz band for the upcoming IEEE 802.11ax standards. Those IEEE 802.11ax devices that are capable of operating in the 6 GHz will be termed as WiFi 6E [128]. But 6 GHz unlicensed spectrum is termed as greenfield spectrum since neither 3GPP nor IEEE standards currently operate in the 6 GHz band [128]. Since NR-U is already LBT enforced, NR-U does not need any further action to coexist with WiFi devices in the 6 GHz band. Moreover, WiFi 6E does not need to be backward compatible like previous versions, and developing coexistence mechanisms to operate in the 6 GHz band for NR-U and WiFi standards opens up new research opportunities. In Table VI, standardization efforts to address a number of coexistence issues between cellular and IEEE 802.11 standards are given below.

TABLE VI
STANDARDIZATION EFFORTS TO NUMEROUS COEXISTENCE ISSUES BETWEEN CELLULAR AND IEEE 802.11 STANDARDS.

Aspect	**LTE-U**	**LAA**	**NR-U**
Standardization working group	LTE-U Forum, 3GPP	3GPP	3GPP
Deployment mode	CA	CA	• CA • DC • Standalone
Operational unlicensed bands	5 GHz	5 GHz	• Sub-7 GHz (i.e., 2.4 GHz, 5 GHz, and 6 GHz) • mmWave bands (i.e., 60 GHz)
Coexistence enabler	CHS, FBS, CSAT, Q-learning, NNT, MMBPP, TPC,	LBT	LBT
Region/countries	The USA, China, South Korea	Worldwide	Worldwide
3GPP Release	Release 12	Release 13, 14, and 15	Release 18

VI. COEXISTENCE CHALLENGE, OPEN PROBLEM, CONVERGENCE, AND FUTURE RESEARCH DIRECTION

A. Coexistence Challenge and Open Problem

Several technical challenges remain unaddressed across different layers for the coexistence of cellular standards (i.e., LTE-U, LAA, and NR-U) and IEEE 802.11 standards (i.e., WiFi and WiGig). Given the similar coexistence fairness criterion and the MAC layer operation to LTE-U/LAA, major challenges discussed in the following due to the coexistence of the cellular and IEEE 802.11 standards are also applicable to NR-U, particularly in the low-frequency 5 GHz unlicensed bands. Unlike LTE-U/LAA, as NR-U operates in the high-frequency 60 GHz unlicensed band, numerous coexistence challenges due to mainly beam-based transmissions in the 60 GHz band for NR-U are also highlighted.

1) Frequency Reuse: In licensed bands, a cellular standard can reuse the same frequency spatially over a certain area to improve spectrum utilization and efficiency by employing proper intercell interference management. This, however, is not the case for unlicensed bands as no such interference management exists between cellular and IEEE 802.11 standards. Moreover, the current LBT does not allow neighboring cellular nodes to transmit simultaneously due to employing contention-based opportunistic scheduling. These result in allowing no simultaneous transmission of cellular and IEEE 802.11 nodes and hence no reuse of the same unlicensed spectrum spatially. Hence, enhancing LBT such that a cellular user can differentiate the signals transmitted from the WiFi and the cellular nodes is an open research problem that is yet to be addressed [6].

2) Design and effectiveness of existing coexistence mechanisms: The main challenge for the coexistence of cellular and IEEE 802.11 standards comes from the design of an efficient coexistence mechanism in the unlicensed band. Major constraints to designing an efficient coexistence mechanism include the lack of inter-RAT coordination, intercell interference management, independent resource allocations from one RAT to another, and different MAC and Physical Layer (PHY) protocols, which makes the inter-RAT coordination a challenging problem [120]. As mentioned earlier, in the case of LTE-U and WiFi systems, LTE uses centralized MAC, whereas WiFi uses contention-based MAC. Further, LTE uses a spectrum bandwidth of up to 100 MHz, whereas WiFi uses a spectrum bandwidth of up to 160 MHz, in the PHY layer. Furthermore, though spectrum is allocated per resource block (i.e., 180 kHz in 1 ms) basis in LTE systems, WiFi uses the whole system bandwidth at a time. Due to these disparities between LTE-U and WiFi systems, extensive modifications are needed to design radio resource management to allow the efficient coexistence of LTE-U and WiFi systems [7].

Moreover, the existing literature mainly focuses on the throughput-based coexistence fairness of cellular and IEEE 802.11 standards [90]. However, with the growing demand for delay-sensitive mobile services, both throughput and delay performances need to be considered in defining coexistence fairness. Existing coexistence mechanisms such as CSAT with a long on period and LBT with a long transmission burst may cause large packet delay and jitter of IEEE 802.11 nodes. Hence, novel coexistence mechanisms are necessary to develop to address the delay-performance of IEEE 802.11 standards [6].

Furthermore, there exists a continuous dispute over the effectiveness of the existing coexistence mechanisms. This is because both CSAT/Blank subframes and LBT are designed for specific markets [14]. For example, CSAT/Blank subframes suffer from their own weaknesses, e.g. the ON/OFF periods for the duty-cycle of CSAT and the non-blank subframe duration of a blank subframe pattern period are controlled by the cellular node LAA and WiFi APs simply adapt to this change, resulting in poor performances of WiFi APs. In this regard, an agreement among the community is needed for one or more acceptable coexistence mechanisms. [14].

3) Lack of documented agreement on fairness definition: The definition of fairness is not clear. According to IEEE 802.11 community (e.g., WiFi community), fairness is defined as the cellular standard (e.g., LAAs) that do not impact WiFi more enormous than one WiFi network [14]. On the contrary, some 3GPP members believe that the total bandwidth should be equally divided among LAA and WiFi standards. In this regard, an agreement is needed on the definition of fairness [14].

4) Radio resource management: Unlike licensed bands, transmissions in unlicensed bands are discontinuous and opportunistic, particularly, for cellular standards using LBT such as LAA and NR-U, which result in reduced efficiency and flexibility in Radio Resource Management (RRM). Further, the interference scenarios in unlicensed bands are not predictable, resulting in increasing the received interference signal level due to opportunistic channel access from WiFi. Hence, how to schedule optimally the unlicensed spectrum at the RB level is a major challenge.

5) Traffic offloading: Due to LBT features, a cellular SC (e.g., LTE-U SC) can not occupy the unlicensed band for a certain duration even if it is required. Hence, the performance of a cellular node on the unlicensed band is time-varying and depends heavily on the channel access activities of other systems. This requires a trade-off measure to provide LTE users with optimized traffic dispatch over different bands [129].

6) Interoperator interference: Because in unlicensed bands different operators have equal priorities, uncoordinated resource management leads to interoperator interference if more than one cellular operators access the same unlicensed spectrum at the same time [7]. This requires negotiation and coordination policies to address interoperator interference, i.e, either to avoid interference for orthogonal spectrum allocations or to mitigate interference for non-orthogonal spectrum allocations [120].

7) Spectrum regulation and network selection: Operating cellular standards (e.g., LTE-U) in the unlicensed bands are subject to satisfying spectrum regulations, e.g., LBT, in countries such as Japan and Europe. While other countries such as China, India, and South Korea do not enforce such spectrum regulations [120]. Note, however, that the introduction of LBT causes efficient spectrum utilization as LBT does not allow cellular nodes to operate at all the time even though demand still holds. The performance of LTE and LBT depends on how other access technologies use the channel that varies with time, resulting in difficulty to ensure guaranteed QoS [120]. Moreover, for the UEs enabled with the multiple unlicensed spectrum bands, it remains unaddressed how to choose the best networks to get access based on their needs [6]?

8) Adapting the energy detection threshold: A major challenge in the NR-U standard is how to set the ED threshold to define channel occupancy. ED defines the channel status in terms of binary 1 or 0, whereas, preamble detection defines the type of devices using the channel. Hence, by knowing the type, the detection threshold can be adapted to address the impact of hidden terminals [14]. Moreover, by adapting the ED threshold value, fairness between NR-U and IEEE 802.11 standards can be improved, while spatial frequency reuse requires further investigation.

9) LBT for beam-based transmissions on the high-frequency 60 GHz unlicensed band: Unlike LTE-U and LAA, since NR-U operates as well in the 60 GHz mmWave band, using beam-based transmissions, LBT used in LAA with omnidirectional transmissions needs additional requirements to be addressed for beam-based NR-U discussed as follows.

a) LBT for beam-based transmissions: In the case of beam-based transmissions, LBT suffers even more than that in LAA due to the hidden node and exposed node problems. Hidden node and exposed node problems arise if directional and omnidirectional carrier senses are used, respectively, while directional beam-based transmissions (like in WiGig) are used. Hence, the effect of the directivity of the carrier sense in LBT for beam-based NR-U operating in the 60 GHz band needs to be studied thoroughly [13].

b) Receiver-assisted LBT: In the case of beam-based transmission, in some situations, interference may not be detected at the transmitting node because listening to the channel at the transmitter may not detect the activity with the carrier sense near the receivers. In such cases, receivers are rather better candidates to estimate potential interference, followed by informing the estimation to the transmitting node to manage interference. Hence, interference mitigation schemes utilizing information from the UE should be considered for the beam-based transmissions [13].

c) Intra-RAT frequency reuse: Since LBT operates based on the ED of the channel in an uncoordinated manner, it causes unnecessary blocking among nodes of the same RAT, which results in reduced spatial reuse and efficiency of the frequency. Hence, a new frequency reuse method is necessary to develop that can address blocking of LBT for the NR-U devices of the same operator or NR-U devices of different operators if coordination between RATs is permitted [13].

d) Congestion window size adjustment: In beam-based transmissions, due to the directionality, some collisions may not be related to the transmit beam for which the Congestion Window Size (CWS) is being updated, for example, collisions due to interference from other directions. This requires defining new procedures for adjusting CWS under beam-based transmission for NR-U [13].

B. Convergence of 3GPP and IEEE Standards

In current deployments, Table VII shows noticeable features of the cellular standard as compared to that of WiFi, which competes with each other after cellular technologies entered recently into the unlicensed spectrum. Even though they differ in numerous critical features and compete with each other to access the unlicensed bands, from the latest versions of the IEEE 802.11ax and 3GPP NR-U, it can be found that both technologies are converging to use large bandwidth in terms of aspects used in the radio access by introducing the best of both standards [32]. For example, WiFi has introduced cellular features such as HARQ and OFDM once

TABLE VII
NOTICEABLE FEATURES OF THE CELLULAR AND IEEE 802.11 STANDARDS.

Feature	**Cellular Standards**	**IEEE 802.11 Standards**
Starting of operations in the unlicensed bands	Recent (2015 with LTE)	Long ago (1997)
Type of spectrum and coverage, respectively, which are designed originally for the operation	Licensed spectrum bands and outdoor coverage, respectively	Unlicensed spectrum bands and indoor coverage, respectively
Operational bandwidth	Small bandwidth	Large bandwidth
Design principle	Originated from its limited and expensive licensed spectrum based on the interference management and coordination principle	Operates exclusively in unlicensed bands based on the principle of interference avoidance

cellular technologies appear to operate in the unlicensed spectrum. Likewise, NR-U adopts a short-length frame structure, flexible access, and spectrum access protocols LBT used in WiFi to get adapt to the characteristics of the unlicensed spectrum [32]. The deployment scenarios to address such convergence may appear in the future in the following ways [32].

- *Non-overlapping coverage*: Both standards operate in the same spectrum but different geographical areas.
- *Overlapping coverage*: Both standards share the same unlicensed spectrum fairly in the same geographical areas
- *Convergence in the RAN:* Both converge in the RAN for overlapping, as well as non-overlapping, deployment areas using cellular and WiFi interworking. In this regard, 3GPP considers two types of integration, namely core network integration so that RANs of both WiFi and cellular can connect to the same 4G/5G core [130] and Radio Acces Network (RAN) level integration such that WiFi AP can directly connect to an anchor cellular BS.
- *Building a single standard*: Both IEEE and 3GPP build a single standard in the next-generation mobile networks, e.g. 6G or 7G.

E. Future Research Directions

1) Interference detection and delay performance: Interference detection is one of the major issues for the coexistence of cellular and WiFi technologies, irrespective of employing LBT features. However, it is also important to keep cellular users' perceived delay within the desired level. This is because a long duty cycle in CSAT to ensure enough sensing duration or long burst in LBT may lead to the increased delay perceived by cellular users. Even though the blank subframes mechanism may reduce cellular user delay due to a small gap between transmissions, a short sensing period may lead to inaccurate channel sensing results. Hence, a tradeoff between interference detection accuracy and cellular user experience is necessary to carry out.

2) Inter-operator spectrum sharing: For SCs of multiple cellular operators operating in the unlicensed spectrum and located in the same place, inter-operator coordination and negotiation are necessary. Even though great attention has already been given to the spectrum sharing between cellular networks operating in the licensed spectrum, spectrum sharing for the cellular networks operating in the unlicensed bands is not yet obvious and is a crucial research direction [7].

3) MAC mechanism: Recall that WiFi uses DCF based on CSMA/CA, which is not sufficient to deal with both intra-operator and inter-operator interference brought by LTE-U because of its static channel access nature [131]. Hence, designing suitable access mechanisms to adapt cellular (i.e., LTE) frame structure with respect to the LBT requirements is an urgent task [132-133]. Given the LTE-U coexistence requirement, how to design a better MAC mechanism for LTE-U is still open to address [131].

4) Traffic loading: In cellular networks, the handover procedure is performed by the macrocells, resulting in reducing the handover signaling overhead between the macrocell and WiFi APs. Due to this reason, some operators have already deployed a large number of WiFi APs to offload some cellular traffic to the unlicensed band. However, to achieve the system performance improvement or cost reduction, more efforts are needed. Hence, traffic offloading for different RATs is difficult to understand and much work is yet to do [131].

5) Integration of mmWave and sub 7 GHz licensed/ unlicensed bands for NR-U: Integration of mmWave and sub 7 GHz bands for NR-U by combining licensed/ unlicensed/shared paradigms under numerous operational modes such as CA is a crucial area for further researches [134].

6) NR-U for URLLC: To understand whether or not NR-U can meet the strict low latency and high-reliability requirements [135], both analytic framework and simulations for NR-U are crucial. In case, NR-U can not meet the requirements for URLLC, what modifications are necessary can be understood [13].

7) NR-U for smart factories: Since industry 4.0 has emerged as an application for 5G NR-U, a major future research direction is to develop theoretical foundations for the licensed, unlicensed, and shared spectrum paradigms to use NR-U as the RAT for future smart factories [13].

8) Ensuring cellular upload transmission: LBT is designed to allow cellular standards such as LAA a fair and efficient medium access with IEEE 802.11 standards such as WiFi. However, sensing channel availability is decided by BSs, whereas upload transmission permission is decided by the terminal user in LTE [131]. Hence, if a user fails to access the channel due to contention while the BS already schedules the user's upload transmission, supporting upload transmission in such a scenario would be difficult. How to ensure upload transmission without changing the centralized scheduling mechanism is a challenging issue [131], and needs considerable research studies.

9) Operation of LBT in the 2.4 GHz: It is recommended by recent technical reports that all sub-7 GHz unlicensed bands are targeted for 5G NR-U, including the 2.4 GHz band. For example, TR 38.889 includes 2.4 GHz for NR-U, unlike LTE-LAA [91]. However, the 2.4 GHz band is already crowded with multiple existing technologies, including Bluetooth, ZigBee, and IEEE 802.11b/g/n/ax. Bluetooth Low Energy (BLE) is a prominent standard and hence, operating LBT in the 2.4 GHz raises new coexistence concerns with the longtime existing BLE. Though the observations from the existing coexistence studies between LBT-based LTE-LAA and WiFi could be extended towards understanding in the 2.4 GHz band, due to differing the channel access protocol of BLE 5 considerably from that of WiFi, these observations are inadequate. This requires a separate evaluation of BLE 5 and LBT coexistence.

In this regard, a recent study [136] is carried out, reporting the mutual impact of BLE 5 and cellular LBT coexisting systems using empirical evaluation by investigating the effects of channel access priorities of LBT and physical layers of BLE. Though the work provides noticeable insights on the coexistence of cellular with BLE 5 in the 2 GHz band, measurements and findings could be expanded further by examining more realistic settings such as the effect of multipath, as well as the effect of other parameters such as BLE connection interval and packet size, for a comprehensive understanding of the performance. Moreover, the effect of heterogeneous LBT channel access priorities in the same channel and across different channels on the BLE network is an interesting research direction [136].

VII. LESSONS LEARNED

Several lessons have been derived from this survey, which is summarized in the following.

- *Unlicensed spectrum bands:* Due to the worldwide large spectrum bandwidth availability (e.g., 9 GHz in Europe and 14 GHz in the USA), the presence of LOS signal components, and the high capacity and data rates at a short distance using directional antennas, the 60 GHz unlicensed spectrum band is preferable to other unlicensed bands, i.e. sub-7 GHz, for the indoor coverage. Note that, for the indoor coverage, particularly, in the USA and Europe, the 6 GHz is also a good candidate band since no unlicensed devices currently operate in the 6 GHz band, and hence there is no need to align channel access protocols for the LTE-LAA with those used by WiFi devices unlike in the 5 GHz band. Moreover, due to the availability of a large amount of spectrum (e.g., 500 MHz in Europe and 1.2 GHz in the USA) in the 6 GHz band, the high capacity demand of future mobile networks can be addressed. For the outdoor coverage, the 2.4 GHz is suitable because of its favorable signal propagation characteristics, as well as its worldwide availability.
- *Coexistence mechanisms:* Coexistence between cellular and IEEE 802.11 standards can be provided based on whether or not introducing a CSMA/CA like carrier sensing mechanism to the existing cellular networks are allowed. If allowed, the LBT mechanism is preferable due to providing better coexistence fairness and meeting global regulations. Otherwise, the CHS mechanism is preferable because of its better performance in coexistence fairness than other mechanisms such as CSAT, acceptance by all regions of the world, and no interference to the WiFi, given that clear channels are available.
- *Coordination:* Typically, coordinated schemes are preferable for the same type of networks, whereas uncoordinated schemes are suitable for different types of networks, in coexistence. Moreover, due to the higher protocol/infrastructure complexities and coordination overheads, even though coordinated schemes show better performances, most existing coexistence schemes are uncoordinated.
- *Condition for fair coexistence:* The fair coexistence between a cellular network (e.g., LTE) and an IEEE 802.11 network (e.g., WiFi) is defined by the 3GPP as follows: *The capability of an LAA network not to impact WiFi networks active on a carrier more than an additional WiFi network operating on the same carrier, in terms of throughput and latency* [55-56]. The same condition is applicable for the coexistence of an NR-U network with a WiFi/WiGig network.
- *Cellular versus IEEE 802.11 technologies:* A cellular technology is an allocation-based mechanism that transmits data continuously using a centralized scheduler. On the other hand, an IEEE 802.11 (e.g., WiFi) technology is a contention-based mechanism that transmits data opportunistically using the CSMA/CA-based DCF. Moreover, unlike a cellular technology (e.g., LTE) that allocates its bandwidth to users after dividing it into RBs at each TTI, WiFi APs occupy the entire bandwidth for a certain amount of time once they get access to the channel [65]. These different MAC layer techniques result in CCI between a WiFi AP and a cellular node when both accessing the same unlicensed spectrum.
- *LBT:* Due to their different channel access mechanisms, a cellular node operating in the same WiFi band may block the transmission of a WiFi AP entirely. This can be avoided by implementing LBT into cellular nodes if operating in an unlicensed band.
- *Regulatory requirements:* Cellular technologies to operate in the unlicensed bands need to satisfy country/region-specific regulatory requirements. For example, while numerous countries, including the USA, China, India, and South Korea, do not require cellular technologies to be LBT enabled, LBT is compulsory for a number of countries/regions, including Japan and Europe. Hence, because LTE-U is not LBT enabled, it can be used in the USA, China, India, and South Korea. Likewise, LAA can be used worldwide due to introducing the LBT mechanism into it.
- *Deployment scenarios:* Cellular standards such as LTE-U and LAA operate in a single unlicensed band (i.e. 5 GHz), whereas NR-U uses multiple unlicensed bands, including both the sub-7 GHz bands, as well as mmWave bands. Besides, along with the CA employed in LTE standards, NR-U standards support both the DC and the standalone operations. DC differs from CA by

the fact that data of a UE can be exchanged simultaneously with more than one gNBs/eNBs in DC in contrast to a single gNB/eNB in CA. This results in the DC to help improve both the throughput, as well as the reliability, unlike the CA that can help improve only the throughout.

- *Standardization efforts:* The first cellular standard operating in the unlicensed bands is LTE-U in the 3GPP Release 12. Another standard of LTE is LAA formalized in Release 13. Recently, 5G NR, specified in Release 15, is being designed by 3GPP by considering operating in the unlicensed bands as an inherent feature through the so-called NR-U in Release 16. In contrast, the standardization for the IEEE 802.11 standards has been carried out by the IEEE. Though existing 802.11 standards use the CSMA/CA by default to avoid collisions, the 802.11ax standard is likely to address this problem by introducing protocols similar to cellular standards.
- *Coexistence challenges:* Designing an efficient coexistence mechanism is the major coexistence challenge to operate cellular with IEEE 802.11 standards. This is because major constraints, including the lack of inter-RAT coordination, intercell interference management, independent resource allocations from one RAT to another, and different MAC and PHY protocols, make the inter-RAT coordination difficult. Further, discontinuous and opportunistic transmissions by LBT enabled cellular standards such as LAA and NR-U result in reducing efficiency and flexibility in RRM. Furthermore, no spatial frequency reuse in the unlicensed bands is possible due to the absence of interference management between cellular nodes and IEEE 802.11 APs, as well as not allowing simultaneous transmissions of neighboring cellular nodes by the current LBT. Besides, NR-U operating in the 60 GHz mmWave band causes LBT to be addressed with additional requirements for the beam-based transmissions.
- *Convergence:* Despite the existence of their strong competitions and the difference in their features, based on the latest versions of the IEEE 802.11ax and 3GPP NR-U, both cellular and IEEE 802.11 standards are converging to use large bandwidth by bringing together the best of both standards.
- *Future research guidelines:* In the following, a few major future research directions are highlighted.
    - ▪ Developing theoretical foundations for the licensed, unlicensed, and shared spectrum paradigms to use NR-U.
    - ▪ Performing a tradeoff between interference detection accuracy and cellular user experience.
    - ▪ Developing unlicensed spectrum sharing techniques for the cellular networks.
    - ▪ Designing appropriate access mechanisms to adapt cellular frame structure with LBT requirements.
    - ▪ Designing a MAC mechanism for the LTE-U standard in accordance with its coexistence requirements.
    - ▪ Designing traffic offloading mechanisms for different RATs, including LTE-U and WiFi.
    - ▪ Developing mechanisms toward the integration of mmWave and sub 7 GHz bands for NR-U by combining licensed, unlicensed, and shared spectrum paradigms.

VIII. CONCLUSION

Due to the disproportionate increase in the available spectrum with the increase of network capacity and data rate demands, as well as their insignificant improvement due to applying existing techniques, MNOs shift the focus from the licensed spectrum only deployment to the unlicensed spectrum bands as well. However, a number of IEEE 802.11 standards-based technologies have already been operating in such unlicensed bands. Since cellular networks do not sense the channel condition before any transmission, a proper *coexistence* mechanism to manage CCI between cellular and WiFi technologies is necessary to operate both technologies in the same unlicensed band. Numerous surveys have already been carried on the coexistence of cellular and IEEE 802.11 standards with a focus on one or more essential concerns, including the unlicensed spectrum band, coexistence mechanism, deployment scenario, transmission technique, regulatory requirement, design principle, potential issue, existing solution, and roadmap for future research. Unlike the existing surveys, in this paper, we have surveyed the coexistence of cellular and IEEE 802.11 standards from a *holistic viewpoint* taking into account the coexistence of *all* existing and future cellular and IEEE 802.11 standards in all unlicensed bands.

In doing so, we have provided an overview of unlicensed spectrum bands, including 2.4 GHz, 5 GHz, 6 GHz, and 60 GHz for cellular technologies, namely LTE-U, LAA, and NR-U, worldwide, as well as reviewed the operation of cellular technologies in the unlicensed spectrum bands. Further, we have summarized scenarios and categories of coexistence mechanisms, conditions for fair coexistence, and coexistence-related features. Furthermore, coexistence mechanisms, deployment scenarios, and standardization efforts for coexistence have been studied followed by highlighting the coexistence challenge and open problem, the convergence of the 3GPP and IEEE standards, and future research directions. Comparative studies of major aspects of a number of key concerns, namely unlicensed spectrum band, regulatory requirement, coexistence mechanism, and cellular standardization effort, have been performed in tabular forms to provide relative measures. Finally, key lessons that have been learned and discussed throughout the paper have been summarized.

The survey in this paper aims at providing a broader view on the coexistence of cellular and IEEE 802.11 technologies in unlicensed bands to introduce relevant diversified concerns based on existing literature to the readers. The focus of this survey is to discuss fundamental aspects for the coexistence of these two established wireless technologies that would lead to generate novel ideas and develop new techniques to address already raised but yet unsolved, as well as forthcoming concerns. Finally, we wish that this survey would take considerable attention of researchers both in academia and industry of similar interests to encourage further research endeavors towards the coexistence of cellular and IEEE 802.11 technologies in unlicensed bands.

APPENDIX I

A LIST OF ABBREVIATIONS

Abbreviation	**Description**
2D	2-Dimensional
3GPP	Third Generation Partnership Project
4G	Fourth-Generation
5G	Fifth-Generation
ABS	Almost Blank Subframe
AFC	Automatic Frequency Coordination
AP	Access Point
BLE	Bluetooth Low Energy
BS	Base Station
CA	Carrier Aggregation
CAPC	Channel Access Priority Classe
CCA	Clear Channel Assessment
CCI	Co-Channel Interference
CHS	Channel Selection
COT	Channel Occupancy Time
C-plane	Control Plane
CSAT	Carrier Sense Adaptive Transmission
CSMA/CA	Carrier-Sense Multiple Access with Collision Avoidance
CTC	Cross-Technology Communication Channel
CWS	Congestion Window Size
D2D	Device-to-Device
DC	Dual Connectivity
DCF	Distributed Coordination Function
DFS	Dynamic Frequency Selection
DL	Downlink
DSRC	Dedicated Short Range Communications
EC	European Commission
ECU	Effective Channel Utilization
ED	Energy Detection
eICIC	Enhanced ICIC
EIRP	Equivalent Isotropic Radiated Power
eNB	Evolve NodeB
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
FBS	Fully Blank Subframe
FCC	Federal Communications Commission
FPP	FBS Pattern Period
FWA	Fixed Wireless Access
gNB	Next Generation NodeB
GT	Game Theory
HARQ	Hybrid Automatic Repeat Request
HetNets	Heterogeneous Networks
HEW	High Efficiency WLAN
HNN	Hopfield Neural Network
ICIC	Inter-cell Interference Coordination
IEEE	Institute of Electrical and Electronics Engineers
ITEL-BA	Iterative Trial and Error Learning-Best Action
ITS	Intelligent Transportation System
LAA	Licensed Assisted Access
LBT	Listen-Before-Talk
LOS	Line-Of-Sight
LPI	Low Power Indoor
LTE	Long-Term Evolution
LTE-U	Long-Term Evolution Unlicensed
MAC	Medium Access Control
MCOT	Maximum Channel Occupancy Time
mmWave	Millimeter-Wave
MNO	Mobile Network Operator
NCB	Nominal Channel Bandwidth
NNT	Neural Networks Technology
NPRM	Notice of Proposed Rulemaking
NR-U	New Radio Unlicensed
OCB	Occupied Channel Bandwidth
OFDM	Orthogonal Frequency-Division Multiplexing
OSDL	Opportunistic Supplemental Downlink
PHY	Physical Layer
PSD	Power Spectral Density
QoE	Quality-of-Experience
QoS	Quality-of-Service
RAN	Radio Acces Network
RAT	Radio Access Technology
RB	Resource Block
RLAN	Radio Local Area Network
RRM	Radio Resource Management
SC	Small Cell
SDL	Supplemental Downlink
SDN	Software Defined Networking
SG	Study Group
TDD	Time-Division Duplex
TDM	Time-Division Multiplexing
TGax	IEEE 802.11ax Task Group
TPC	Transmit Power Control
TTI	Transmission Time Interval
UE	User Equipment
UHF	Ultra High Frequency
UL	Uplink
UNII	Unlicensed National Informational Infrastructure
U-plane	User Plane
VHF	Very High Frequency
VLP	Very Low Power
WAS	Wireless Access System
WG	Working Group
WiFi	Wireless Fidelity
WiGig	Wireless Gigabit
WLAN	Wireless Local Area Network

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