On Operating Cellular Technologies in Unlicensed Spectrum Bands: A Review

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***Abstract*—In this paper, we provide a brief, yet reasonably broad in scope, review on the coexistence of cellular and IEEE 802.11 standards, which takes into account the coexistence of all existing and future cellular standards in all available unlicensed spectrum bands. In particular, the paper summarizes key things, including coexistence fairness, related features, regulatory requirements, design principles, mechanisms, deployment scenarios, challenges, and convergence, necessary for the coexistence of cellular technologies in the unlicensed bands.**

Keywords-Unlicensed band; review; cellular network; WiFi; coexistence.

I. INTRODUCTION

The scarcity of radio spectrum has been a major bottleneck in cellular mobile communications [1]. An increase in high capacity and data rate demands due to the recent growth of mobile data traffic puts a further burden on the licensed spectrum of a Mobile Network Operator (MNO). Even though several attempts have been taken to address the spectrum scarcity issue, e.g., improving the utilization of the licensed spectrum, the situation has not been improved considerably. This causes MNOs to seek alternative solutions, and operating as well in the unlicensed bands has been found effective due to the availability of a large amount of spectrum in the unlicensed bands.

Numerous studies [2]-[6] have already been carried on the coexistence of cellular and Institute of Electrical and Electronics Engineers (IEEE) 802.11 standards taking into account one or more of the following aspects, including the unlicensed spectrum band, coexistence mechanism, transmission mode, deployment scenario, regulatory requirement, design principle, and potential issue. For example, the authors in [3] studied Long-Term Evolution (LTE)-Licensed Assisted Access (LAA) and Wireless Fidelity (WiFi) coexistence in the 5 GHz with the corresponding deployment scenario. Similarly, in [4], the authors presented a coexistence study of Wi-Fi and LTE-in-unlicensed by surveying a large parameter space of coexistence mechanisms and a range of representative network densities and deployment scenarios. Nevertheless, in [5], emphasizing unlicensed Millimeter-Wave (mmWave) bands, as well as considering the beam-based transmissions, the authors presented an overview of the major design principles and solutions to operate New Radio Unlicensed (NR-U) in unlicensed bands.

Different from these above studies, in this paper, we provide a brief review on the coexistence of cellular and IEEE 802.11 standards by taking into account the coexistence of all existing and future cellular standards in all available unlicensed bands. Based on the existing literature, fundamental aspects for the coexistence of these two established wireless technologies, including coexistence fairness, related features, regulatory requirements, design principles, mechanisms, deployment scenarios, challenges, and convergence, are summarized. The detailed discussion on each aspect of the above aspects is out of the scope of this paper. However, for further information, a list of references is given in the end so that interested readers may refer to these references corresponding to any fundamental aspect mentioned alongside while discussing in this paper.

The paper is organized as follows. Section II covers the discussion on the available unlicensed bands for the operation of cellular technologies. The condition for fair coexistence, as well as coexistence-related features, are discussed in Section III. Coexistence mechanisms and deployment scenarios are reviewed in Section IV and Section V, respectively. Finally, we highlight technical challenges and convergence of coexistence in Section VI. We conclude the review in Section VII.

II. CELLULAR TECHNOLOGIES IN UNLICENSED BANDS

Cellular technologies may operate in one or more unlicensed spectrum bands, including 2.4 GHz, 5 GHz, 6 GHz, and 60 GHz. Due to the similar propagation characteristics, 2.4 GHz, 5 GHz, and 6 GHz are termed as sub-7 GHz, whereas 60 GHz as mmWave, bands. The first cellular-based technology extended with a view to operating only in the 5 GHz unlicensed spectrum is the Fourth-Generation (4G) LTE in 2015. The two variants of LTE in the unlicensed band are LTE Unlicensed (LTE-U) in the Third Generation Partnership Project (3GPP) Release 12 [7] and LAA in 3GPP Releases 13, 14, and 15 [8]-[12].

However, operations in the mmWave have been permitted recently starting first with the Fifth-Generation (5G) NR-U [5], [13] technology in 3GPP Release 16.

 ISBN: 978-1-61208-895-2

Recently, Federal Communications Commission (FCC) approved the 6 GHz band in the USA for spectrum sharing [14]. Likewise, Europe is considering allowing the 6 GHz band to use [15]. 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 [5], [16]. Hence, unlike LTE-U and LAA, NR-U supports multiple unlicensed bands, including sub-7 GHz and mmWave bands.

III. Coexistence Fairness and Related Feature

A major concern that is faced by each cellular technology is the Co-Channel Interference (CCI) from the incumbent IEEE 802.11 technologies operating in these unlicensed bands. This requires a proper and fair coexistence of cellular with IEEE 802.11 technologies. 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* [17], [18]. Likewise, for NR-U, the coexistence requirement with WiFi/Wireless Gigabit (WiGig) remains the same as that in LAA [16]. However, it is to be noted that many 3GPP members might believe that fairness means cellular nodes and IEEE 802.11 Access Points (APs) should have half of the bandwidth.

Developing a coexistence mechanism is challenging and hence knowledge about the coexistence-related features of both technologies, namely channel access mechanisms, Medium Access Control (MAC) protocols, design principles, and regulatory requirements, reasoned as follows, are crucial.

- *Channel access mechanisms*: Since cellular technologies do not listen to the channel condition when scheduling resources and IEEE 802.11 technologies use the contention-based protocol to access a channel, it is not unusual that cellular nodes may block transmission of WiFi APs completely [3].
- *MAC protocols*: Cellular technology uses continuous transmission of data in consecutive frames using a centralized scheduler. However, WiFi technology uses opportunistic transmission using the Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol [7] to get access to an unlicensed channel. Due to this disparity in MAC layer procedures, WiFi APs may get blocked by a cellular node as the interference level of a cellular network is likely to be above the threshold used by a WiFi network to detect the vacancy of a channel. Likewise, Because WiFi packets are transmitted always with maximum power, if WiFi APs can get access to a channel, they can cause interference to a cellular network.
- *Design principles*: Cellular technology, such as LTE is designed with an assumption that LTE can transmit with a small-time gap continuously and periodically. However, WiFi is designed to coexist with other technologies through random backoff and channel sensing, which allows a WiFi AP a little chance to sense a clear channel and transmit. Due to this reason, a WiFi AP moves to the silence mode causing its performance degradations, while any LTE node remains almost unaffected [3].
- *Regulatory requirements*: Regulatory requirements to operate different cellular technologies in unlicensed bands vary from one country or region to another. For example, though countries such as the USA, China, India, and South Korea [3] do not require cellular technologies such as LTE to be Listen-Before-Talk (LBT) enabled, LBT is mandatory in Japan and Europe. LBT is a contention-based medium access technique similar to the CSMA/CA mechanism used by WiFi [5], meaning that LBT does not allow a cellular node to occupy a channel at all times. Since LTE-U does not implement the LBT mechanism, it can be used in the USA, China, India, and South Korea. Instead, as LAA is LBT enabled, LAA can be used worldwide [3].

IV. Coexistence Mechanism

Coexistence mechanisms can be developed in two ways depending on whether or not modifications on the existing cellular networks are employed. If modifications are employed, a cellular network is enabled with the LBT mechanism to avoid CCI with other existing transmissions by backing off or moving to another channel. 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] to avoid CCI. Since LAA is LBT enabled, this approach is used in LAA.

On the other hand, if modifications are not employed, a cellular network cannot be enabled with LBT. Numerous coexistence mechanisms without employing LBT have been proposed by exploiting different domains to manage CCI, particularly, Channel Selection (CHS) in frequency-domain [19], [20], Carrier Sense Adaptive Transmission (CSAT) [20], [21] and Fully Blank Subframe (FBS) [22], [23] in time-domain, and Transmit Power Control (TPC) in power-domain [24], [25], [26]. A key feature of each of these mechanisms is that none requires modifications on existing cellular networks.

In the frequency and time domains, the principle of coexistence is based on maintaining the orthogonal transmission of each coexisting node in frequency and time, respectively [27], [28], [29]. In other words, only one node, i.e., either a WiFi AP or a cellular node, can transmit at a time to avoid a collision. However, in the power domain, CCI can be controlled by applying the power control method (i.e., adjusting the output power) to cellular nodes [24], [25], [26]. As LTE-U is not LBT enabled, this approach can be used in LTE-U by exploiting any domain.

Besides, since in practice, the WiFi traffic is bursty, it results in a huge amount of white spaces between WiFi frames. WiFi white spaces create a huge source of spectrum for cellular technologies such as LTE-U [30] that can exploit these white spaces to transmit opportunistically. In this regard, Markov Modulated Batch Poisson Process Model [30] and Reinforcement Learning Technique [31] are examples of approaches to exploit WiFi white spaces. Further, Neural Networks Technology [32] and Graph-based mechanisms [33] can also be employed to enable the coexistence between cellular and IEEE 802.11 technologies in the unlicensed spectrum.

V. COEXISTENCE DEPLOYMENT SCENARIO

Because the supported enabling technologies, including Carrier Aggregation (CA), Dual Connectivity (DC), and standalone operation, of one cellular standard vary from the other, coexistence deployment scenarios of cellular standards vary accordingly. For example, using the CA technology, three deployment scenarios for LTE-U standard in heterogeneous networks [34] and four deployment scenarios for Small Cells (SCs) in LAA [35] are defined by 3GPP. Since NR-U can exploit the DC and standalone operation additionally, five deployment scenarios are defined by 3GPP for NR-U [16], [36].

It is to be noted that DC and CA modes play major roles in connecting User Equipments (UEs) over unlicensed bands. In DC, data of a UE can be exchanged simultaneously with more than one Next Generation NodeBs (gNBs)/Evolve NodeBs (eNBs) [36]. However, in the CA, data of a UE can be exchanged simultaneously with a gNB/eNB through multiple contiguous or noncontiguous bands [36]. Due to this reason, 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 [36]. This implies a major improvement for the deployment of NR in unlicensed bands with respect to that of LTE-U and LAA. In Table I, numerous aspects of 3GPP-based different cellular standards are compared.

VI. COEXISTENCE CHALLENGE AND CONVERGENCE

A. *Coexistence Challenge*

Several technical challenges remain unaddressed across different layers for the coexistence of cellular standards and IEEE 802.11 standards. Few key challenges are as follows.

- The main challenge for the coexistence of cellular and IEEE 802.11 standards comes from the major constraints to design an efficient coexistence mechanism, including the lack of inter-Radio Access Technology (RAT) coordination, intercell interference management, independent resource allocations from one RAT to another, and different MAC and Physical Layer (PHY) protocols [34].

TABLE I
COMPARISON OF NUMEROUS ASPECTS OF DIFFERENT CELLULAR STANDARDS

Aspect	LTE-U	LAA	NR-U
Standardized Bodies	3GPP and LTE-U Forum	3GPP	
Deployment mode	CA		CA, DC, and Standalone
Unlicensed bands	5 GHz		2.4 GHz, 5 GHz, 6 GHz, and 60 GHz
Coexistence mechanism	CHS, FBS, CSAT, and TPC	LBT	
Usage regions	The USA, China, South Korea	Worldwide	
3GPP Release	12	13, 14, and 15	18

- There exists a continuous dispute over the effectiveness of the existing coexistence mechanisms. For example, CSAT/FBS suffer from their weaknesses, i.e., ON/OFF periods for the duty-cycle of CSAT and non-blank subframe duration of an FBS pattern period are controlled by the cellular node, and WiFi APs adapt to this change, resulting in poor WiFi performances [3].
- In unlicensed bands, no interference management like in the licensed bands exists between cellular and IEEE 802.11 standards. Moreover, the current LBT does not allow neighboring cellular nodes to transmit simultaneously due to employing the contention-based opportunistic scheduling [37]. These result in allowing no simultaneous transmission of cellular and IEEE 802.11 nodes, and hence no reuse of the same unlicensed spectrum spatially.
- 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) [37].
- Interference scenarios in unlicensed bands are not predictable [37], resulting in increasing received interference signals due to opportunistic channel access from WiFi.
- Unlike LTE-U and LAA, since NR-U operates as well in the 60 GHz mmWave band, using beam-based transmissions [5], LBT used in LAA with omnidirectional transmissions needs additional requirements to be addressed for beam-based NR-U.

B. *Coexistence Convergence*

Even though they differ in numerous critical features and compete with each other to access unlicensed bands, from the latest versions of the IEEE 802.11ax and 3GPP NR-U, it can be found that both technologies are converging

 ISBN: 978-1-61208-895-2

to use large bandwidth in terms of aspects used in the radio access by introducing the best of both standards [13]. For example, WiFi has introduced cellular features such as Hybrid Automatic Repeat Request (HARQ) and Orthogonal Frequency-Division Multiplexing (OFDM). Likewise, NR-U adopts a short-length frame structure, flexible access, and LBT protocol used in WiFi to get adapt to the characteristics of unlicensed bands [13].

VII. CONCLUSION

In this paper, we have given a brief review of fundamental aspects for the coexistence of cellular and IEEE 802.11 standards. Unlike existing studies, the coexistence of all existing and future cellular standards in all available unlicensed spectrum bands has been considered. We have covered reasonably broad features necessary to understand the coexistence of cellular technologies in the unlicensed bands, including coexistence fairness, related features, regulatory requirements, design principles, mechanisms, deployment scenarios, challenges, and convergence, concisely. Based on the existing literature, the review in this paper aims at introducing readers to the key aspects for the coexistence of these two established wireless technologies in unlicensed bands.

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