Unlicensed Spectrum Bands for Cellular Mobile Networks-An Overview

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***Abstract*—This paper provides a survey on the available unlicensed spectrum bands for cellular mobile networks. Unlicensed spectrum bands in both the sub-7 GHz, including 2.4 GHz, 5 GHz, and 6 GHz, as well as millimeter-wave, including 60 GHz, for the current and future mobile networks, are discussed. Major aspects of each unlicensed band, notably operational region, regulatory requirement, existing technology, available bandwidth, spectrum range, benefit, and challenge are surveyed. A comparative framework, including these above aspects, is then developed in a tabular form to find an appropriate unlicensed spectrum band corresponding to each aspect. Finally, we point out the major benefits and challenges of operating cellular mobile networks on unlicensed bands.**

Keywords-Unlicensed band; survey; cellular network; millimeter-wave.

I. INTRODUCTION

Radio spectrum is limited and not allocated to a Mobile Network Operator (MNO) in proportionate with its traffic demand [1]. To address the scarcity of the available licensed spectrum, techniques, including cell splitting and small cell deployment, have been proposed [2]. However, due to employing such techniques, no noticeable impact has been observed, which causes the focus of MNOs to shift from the licensed-only spectrum to the unlicensed spectrum. Recently, the operations of the Third Generation Partnership Project (3GPP)-based cellular technologies in the unlicensed bands have 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 [3], of these, 2.4 GHz, 5 GHz, and 60 GHz bands are available worldwide [4], whereas the 6 GHz band is currently available in Europe and the USA. In addition to these above-unlicensed bands, cellular technologies, particularly, Fifth-Generation (5G) New Radio Unlicensed (NR-U) can also use shared bands, including 3.5 GHz and 37 GHz, only in the USA [5]. Due to not having a significant difference in signal propagations, according to the 3GPP, 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 millimeter-wave (mmWave) bands. These two unlicensed frequency ranges are targeted for 5G NR-U operations [6].

Typically, an unlicensed spectrum is used by the Institute of Electrical and Electronics Engineers (IEEE) 802.11, also termed as Wireless Fidelity (WiFi) [7], technologies in addition to Bluetooth and ZigBee. 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 modifications on the existing cellular networks are employed. If modifications are employed, a cellular network is enabled with a carrier sensing mechanism, termed as Listen-Before-Talk (LBT).

LBT is a contention-based medium access technique that shares a channel between a cellular node and a WiFi Access Point (AP) fairly [8] by enabling a cellular node to stop periodically its channel occupancy to help avoid CCI due to the coexistence with the WiFi AP. Likewise, numerous coexistence mechanisms without employing LBT have been proposed to manage CCI such as channel selection, carrier sense adaptive transmission, fully blank subframe, and transmit power control. In channel selection, a cellular node measures the level of interference on each channel by detecting the channel's energy so that the data transmission can be made over a channel with the minimum level of interference. In carrier sense adaptive transmission, by dividing time into cycles each consisting of an on period and an off period such that a cellular node can transmit data during the on-state of a cycle. Likewise, in the fully blank subframe, time is segmented into transmission time intervals (TTIs) such that a cellular node can use a set of TTIs over a certain period *T*, whereas, IEEE 802.11 standards can transmit using the remaining number of TTIs in *T* orthogonally to each other in time. A key feature of each of these mechanisms is that none requires modifications on existing cellular networks. Since our focus is mainly on the unlicensed bands for cellular networks, a detailed discussion on coexistence mechanisms is out of the scope of this paper.

Numerous existing works addressed the operation of cellular standards such as Long-Term Evolution Unlicensed (LTE-U), Licensed Assisted Access (LAA), and NR-U on unlicensed bands from specific viewpoints, including coexistence mechanisms [9]-[19], unlicensed bands (e.g., 5

GHz [20]-[22], 6 GHz [23], and 60 GHz [24]), coexistence studies [25]-[26] and scenarios [27], fairness conditions [28]-[29], standardization efforts [30], challenges, and open problems [3] [31]. Different from these above existing studies, in this paper, we provide a survey on unlicensed spectrum bands from a nonspecific viewpoint that takes into account all available unlicensed spectrum bands in both the sub-7 GHz, including 2.4 GHz, 5 GHz, and 6 GHz, as well as mmWave, including 60 GHz, for the cellular networks. Major aspects of each unlicensed band, including operational region, regulatory requirement, existing technology, available bandwidth, spectrum range, benefit, and challenge, are discussed. A comparative framework of all these aspects is then developed, and major benefits and challenges regarding the operation of cellular networks on unlicensed bands are pointed out.

The paper is organized as follows. In Section II, an overview of unlicensed spectrum bands, including 2.4 GHz, 5 GHz, 6 GHz, and 60 GHz, for cellular networks, as well as a comparative framework for a number of major aspects among these unlicensed bands are given. In Section III, the operation of cellular technologies, including LTE-U, LAA, and NR-U, in unlicensed bands is discussed. Key benefits and challenges of operating cellular networks in the unlicensed band are identified in Section IV. We conclude the paper in Section V. A list of abbreviations is given in Appendix I.

II. Overview of Unlicensed Spectrum Bands for Cellular Technologies

A. 2.4 GHz Unlicensed Band

The 2.4 GHz band is the first unlicensed band released by the Federal Communications Commission (FCC) for commercial use and is currently the most utilized unlicensed shared band [8]. 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 [32]. 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) [32], and channel 14 is available only in Japan.

B. 5 GHz Unlicensed Band

The use of the 5 GHz band depends on its requirement in a country [20]. The 5.15-5.35 GHz band is available in the USA, China, South Korea, Europe, Japan, and India; the 5.47-5.725 GHz is available in the USA, South Korea, Europe, and Japan; and the 5.725-5.85 GHz is available in the USA, China, South Korea, and India [7]. Additionally, the 5.35-5.47 GHz and the 5.85-5.925 GHz unlicensed spectra are being considered to make available in the USA and Canada [3] [7] [8]. Moreover, European Commission (EC) also recently proposed to use the 5.725-5.85 GHz spectrum band [8]. In general, due to the clearer channel condition, wider spectrum, and easier implementation [8], the 5 GHz band is considered favorable to other unlicensed bands.

C. 6 GHz Unlicensed Band

The 6 GHz spectrum band is available from 5.925 to 6.425 GHz in Europe, whereas from 5.925 to 7.125 GHz in the USA [23]. Recently, 5.925-6.425 GHz [33] spectrum and 5.925 GHz-7.125 GHz spectrum have been proposed, respectively, by the EC and the FCC under part 15 rules for the unlicensed access [34]-[35]. 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. 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 by unlicensed users to protect licensed services. Unlicensed users are also required to control the transmit power and restrict their coverage to indoors [6].

D. 60 GHz Unlicensed Band

The 60 GHz band is considered for the NR-U to provide directional communications using beamforming to overcome propagation constraints [36]-[37]. Due to operating Wireless Gigabit (WiGig) in the 60 GHz band, the NR-U standard needs to coexist fairly with the WiGig standard. The 60 GHz band ranges from 57 GHz to 71 GHz [38]. The bandwidth available in the unlicensed 60 GHz band is more than that of the aggregate bandwidth of all the other unlicensed bands [39]. 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 [39]. Due to this reason, the 60 GHz band is suited for serving high data rate demand in magnitudes of Gbps over short distances.

III. Cellular Technologies in the Unlicensed Spectrum Bands

Long-Term Evolution (LTE) is the first cellular-based technology extended with a view to operating in the sub-7 GHz unlicensed spectrum bands in 2015, whereas NR-U is the first cellular-based technology that includes operations in the mmWave unlicensed bands [4]-[5]. Hence, since cellular technologies in the previous generations, i.e., Fourth-Generation (4G) LTE, were not allowed to use mmWave bands, two standards of LTE working in the unlicensed bands, namely LTE-U and LAA, operate in the 5 GHz band. However, 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 [4]. Moreover, like LTE, there are a number of

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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. On the other hand, MulteFire is developed by the MulteFire Alliance considering a Standalone deployment in the unlicensed bands using an LBT-based channel access scheme [40].

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 [4], e.g., the use of LBT to 3GPP technologies developed in line with Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) inherent to the IEEE 802.11 technologies. Table I shows comparisons in terms of numerous aspects among 2.4 GHz, 5 GHz, 6 GHz, and 60 GHz unlicensed spectrum bands. From Table I, it can be observed that a total of about 2 GHz unlicensed bandwidth is available below 7 GHz for omnidirectional communications at the 2.4 GHz, 5 GHz, and 6 GHz bands [34]. 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 [41]-[42].

IV. Major Benefits and Challenges from Operating Cellular Networks in the Unlicensed Bands

A. Benefits to Operate in the Unlicensed Bands

By operating cellular networks such as LTE and NR in the unlicensed bands, significant benefits in several aspects can be achieved. A few noticeable benefits are discussed in the following.

1) High capacity, spectral efficiency, and data rates: Employing the Carrier Aggregation (CA) technology, along with the allocated licensed spectrum to an MNO of a cellular network, the unlicensed spectrum can also be used to serve user traffic [8]. Due to the addition of the unlicensed spectrum, the combined spectrum bandwidth of an MNO increases. Moreover, due to the availability of an enormous amount of spectrum bandwidth in the 60 GHz mmWave band, the aggregate bandwidth of an MNO can be increased even further. Since the mmWave spectrum is inherently path loss limited, the 60 GHz unlicensed spectrum is suitable to use within indoor environments. Because the capacity is directly proportional to the available channel bandwidth, the use of the unlicensed spectrum in a cellular network helps increase its overall capacity, spectral efficiency, as well as data rates per user.

2) Data offloading: Given that small cells operate in both the licensed and unlicensed bands, using the CA

TABLE I
A COMPARATIVE FRAMEWORK OF UNLICENSED BANDS FOR CELLULAR TECHNOLOGIES.

Features	**Unlicensed spectrum bands**			
	2.4 GHz	**5 GHz**	**6 GHz**	**60 GHz**
Classification	Mid-bands (sub-7 GHz)	Mid-bands (sub-7 GHz)	Mid-bands (sub-7 GHz)	High-bands (mmWave)
Availability	Worldwide	Worldwide	Europe and the USA	Worldwide
Regulatory requirement	The maximum data rate, multiple access methods, digital modulation scheme, maximum coverage distance, and media access protocol [43]	The maximum in-band output power, out-of-band and spurious emissions, DFS, LBT, and Transmit Power Control (TPC) [44]	DFS, AFC, TPC, and indoor coverage [6]	Short-range communication, Equivalent Isotropic Radiated Power (EIRP), EIRP densities, maximum power, and antenna gains [45]-[46]
Existing technologies	802.11b/g	802.11a/n	Licensed microwave links, fixed satellite systems, and mobile services	802.11ad/ay
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)	Release 16 (5G NR-U)
Available bandwidth	About 100 MHz [47]	500 MHz [7]	500 MHz (Europe) and 1200 MHz (USA) [34]-[35]	9 GHz (Europe) and 14 GHz (the USA)
Spectrum range	2.40-2.50 GHz [47]	5.150-5.925 GHz [7]	5.925-7.125 GHz [5]	57-66 GHz [39]
Antenna pattern	Omnidirectional [34]	Omnidirectional [34]	Omnidirectional [34]	Directional [41]-[42]
Constraints	• Heavily congested • lower data rate	• Lower coverage • Higher penetration and path losses	• Lower coverage • Higher penetration and path losses	• Extremely high penetration and path losses • Blocking
Advantages	• Most utilized unlicensed shared band • Favorable signal propagation characteristics	• Availability of a large amount of spectrum bandwidth • The majority of IEEE 802.11-based technologies operate in this band	• No unlicensed devices now operate [23] • The high capacity demand of future mobile networks can be addressed	• Large spectrum bandwidth availability • High capacity and data rates at a short distance indoors

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technology, an MNO can configure its indoor small cells to offload all or a major portion of its user traffic over the unlicensed spectrum, whereas to serve its control signals over the licensed spectrum, when its user traffic demand is high. If, however, indoor small cells of an MNO are not CA enabled, in that case, its small cells can serve only the user data traffic over the unlicensed spectrum, whereas its macrocell can serve the control signals over the licensed spectrum, given that proper coordination exists between the macrocell and indoor small cells of the MNO.

3) Cost-efficiency: Spectrum licensing fee is very expensive and contributes a great portion to the cost to transmit per bit, i.e. cost efficiency, of an MNO. As there is no cost from using an unlicensed spectrum, by operating an MNO in both the licensed and unlicensed spectrum bands, the demand for high capacity and data rates per user of the MNO can be served at a low average cost per bit transmission, resulting in improving its cost-efficiency.

B. Challenges to Operate in the Unlicensed Bands

Several technical challenges remain unaddressed across different layers for the operation of cellular standards (i.e., LTE-U, LAA, and NR-U) and IEEE 802.11 standards (i.e., WiFi and WiGig) in the same unlicensed band. A few noticeable challenges are discussed in the following.

1) Efficient coexistence mechanism: The main challenge to operate cellular standards in the unlicensed band comes from the design of an efficient coexistence mechanism of cellular and IEEE 802.11 standards in the unlicensed band. Major constraints to designing an efficient coexistence mechanism include the lack of inter-Radio Access Technology (RAT) coordination, intercell interference management, independent resource allocations from one RAT to another, and different Medium Access Control (MAC) and Physical Layer (PHY) protocols [31].

2) Physical and MAC layer procedures of cellular and IEEE 802.11 technologies: Though 3GPP based cellular and IEEE 802.11 technologies use the same Orthogonal Frequency Division Multiplexing (OFDM) and Multiple-Input Multiple-Output (MIMO) techniques in the physical layer, other features, including the transmission power, Modulation and Coding Scheme (MCS), and error correction code, are different [48]. Moreover, cellular standards use Radio Link Control Layer with Hybrid Automatic Repeat Request (HARQ), whereas, WiFi, for example, uses Automatic Repeat Request (ARQ) mechanisms, for the recovery of packet losses.

Further, in the case of the MAC layer procedure, cellular technology is an allocation-based mechanism, whereas an IEEE 802.11 (e.g., WiFi) technology is a contention-based mechanism. Cellular technology uses continuous transmission of data in consecutive frames using a centralized scheduler. But, a WiFi technology uses opportunistic transmission using Distributed Coordination Function (DCF). DCF uses the CSMA/CA protocol to detect the energy level in order to get access to a channel. Due to the CSMA/CA behavior, once WiFi APs gain channel access, they occupy the entire bandwidth for a certain amount of time. Conversely, in a cellular technology such as LTE, 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 [49]. Due to these disparities given above in the MAC layer procedures, CCI between a WiFi AP and a cellular node occurs when both accessing the same unlicensed spectrum.

3) Interference management: Since no interference management exists between cellular and IEEE 802.11 standards, and the current LBT does not allow neighboring cellular nodes to transmit simultaneously due to employing contention-based opportunistic scheduling, no simultaneous transmission of cellular and IEEE 802.11 nodes are allowed, and hence no reuse of the same unlicensed spectrum spatially is possible.

4) Transmission mode: 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).

5) Beam-based transmissions: 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 the beam-based NR-U.

V. CONCLUSION

This paper has presented an essential survey on unlicensed spectrum bands considered for the operation of cellular mobile networks. Particularly, both sub-7 GHz (i.e., 2.4 GHz, 5 GHz, and 6 GHz) bands and millimeter-wave bands (i.e., 60 GHz) proposed for the Fifth-Generation (5G) and beyond networks have been discussed. Each unlicensed band has been surveyed taking into account the classification, operational region, regulatory requirement, existing technology, available bandwidth, spectrum range, benefit, and challenge. A comparative framework in a tabular form has been developed for numerous aspects to compare one unlicensed band to another to find an appropriate unlicensed spectrum band corresponding to a particular aspect. Finally, we have pointed out major benefits and challenges to operate cellular networks in unlicensed bands.

This paper can serve as a source of fundamental knowledge on unlicensed spectrum bands for cellular technologies and be useful for those who aim at working on the operation of cellular networks in the unlicensed spectrum bands. For more details, interested readers are recommended to refer to the existing works cited throughout the paper and given in the reference section.

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