ICSNC 2021: The Sixteenth International Conference on Systems and Networks Communications
October 03 - October 07, 2021 – Barcelona, Spain

On Operating Cellular Technologies in Unlicensed Spectrum Bands: A Review

Author: Rony Kumer Saha

Presented by
Rony Kumer Saha, Ph.D.
Radio and Spectrum Laboratory
Future Network Infrastructure Division 2
ADVANCED TECHNOLOGY LABORATORY

KDDI Research

KDDI Research, Inc. JAPAN
2-1-15 Ohara, Fujimino-shi, Saitama, 356-8502
email: ro-saha@kddi-research.jp

IARIA

Resume of the Presenter

RONY KUMER SAHA received the B.Sc. degree in electrical and electronic engineering from the Khulna University of Engineering and Technology, KUET, in 2004, the M.Eng. degree in information and communications technologies from the Asian Institute of Technology (AIT), Thailand, in 2011, and the Ph.D. degree in electrical engineering from Chulalongkorn University, Thailand, in 2017. Since 2017, he has been working as a Postdoctoral Fellow/Research Engineer with the Radio and Spectrum Laboratory, KDDI Research, Inc., Japan.

He worked as a Lecturer and later promoted to an Assistant Professor with American International University-Bangladesh, Bangladesh, AIUB, from January 2005 to August 2013. From September 2013 to July 2014, he was with East West University, Bangladesh. His current research interests include 5G and beyond ultra-dense HetNets, spectrum sharing, policy, and management in multiple communication systems, and millimeter-wave communications. He has research experiences on mobile wireless communications in universities and industries for more than ten years. He has authored about 60 peer-reviewed, reputed, and highly recognized international journal and conference papers. He also filed an international patent.

Dr. Saha served as a member of the Fronthaul Working Group, xRAN Forum, USA. He also served as a TPC member of the 2020 ICSNC and 2018 IEEE Global Communications Conference Workshops. Furthermore, he also served as the Session Chair for two sessions, namely Radio Resource Management and Aerial Networks at 2019 IEEE VTC-Fall, Hawaii, USA, as well as the 2019 IEEE International Symposium on Dynamic Spectrum Access Networks Newark, NJ, USA, for the session Spectrum Sharing in 5G. Since early 2019, he has been serving as an Associate Editor of the Engineering Journal, Thailand. He served as a Reviewer of a number of recognized journals, including IEEE Transactions on Vehicular Technology, IEEE Access, Elsevier Physical Communication, Wiley International Journal of Communication Systems, MDPI Sensors Journal, MDPI Symmetry Journal, Hindawi Mobile Information Systems, and MDPI Sustainability Journal.

Topics of Research Interests

- Terahertz and millimeter wave communications
- 5G NR-U: 5G New Radio on Unlicensed Bands
- Dynamic spectrum sharing and policy for 5G and beyond mobile networks
- Cognitive radio networks and spectrum sensing techniques
- Co-channel interference analysis, mitigation, avoidance, and cancellation strategies
- In-building small cell network planning, design and deployment
- Planning, design and development of spectrum sharing algorithm for homogeneous (mobile networks) and heterogeneous networks (mobile networks and satellite networks)
- Radio resource allocation and scheduling policy and algorithm
- Mobile MAC layer and physical layer issues
- Proof-of-concept evaluation of virtualization and Slicing of 5G radio access network (RAN)
- Cloud RAN (CRAN) in 5G era
- Fronthaul design for CRAN

Presentation Outline

- Background and Problem Statement
- Cellular Technologies in Unlicensed bands
- Coexistence Fairness and Related Feature
- Coexistence Mechanism
- Coexistence Deployment Scenario
- Coexistence Challenge and Convergence
- Conclusion
- References

Background and Problem Statement

The scarcity of radio spectrum has been a major bottleneck in cellular mobile communications [1]. Even though several attempts have been taken to address the spectrum scarcity issue, the situation has not been improved considerably. This causes MNOs to seek alternative solution, 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 in the unlicensed bands, 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.

Different from these 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.

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.
- 2.4 GHz, 5 GHz, and 6 GHz are termed as sub-7 GHz, whereas 60 GHz as millimeter-wave (mmWave), bands.
- The first cellular-based technology operating in the 5 GHz unlicensed spectrum is the LTE. The two variants of LTE are LTE Unlicensed (LTE-U) and LAA [8]-[12].
- Operations in the mmWave have been permitted recently starting first with the NR-U technology [5], [13] .
- Recently, Federal Communications Commission (FCC) approved the 6 GHz band in the USA [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 where the provision for NR-U 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.

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*.

Coexistence Fairness and Related Feature (2)

Developing a coexistence mechanism is challenging and hence *knowledge about the coexistence-related features of both technologies 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.**

Coexistence Fairness and Related Feature (3)

- *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].**

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.

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].

Coexistence Mechanism (2)

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].

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.

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].

In Table I, numerous aspects of 3GPP-based different cellular standards are compared.

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

Coexistence Challenge and Convergence

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].

- 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].

Coexistence Challenge and Convergence (2)

- **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.**

Coexistence Challenge and Convergence (3)

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 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].

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.

References

1. R. K. Saha, “On Maximizing Energy and Spectral Efficiencies Using Small Cells in 5G and Beyond Networks,” Sensors, vol. 20, no. 6, art no. 1676, 2020.
2. J. Zhang et al., “LTE on License-Exempt Spectrum,” IEEE Commun. Surveys Tuts., vol. 20, no. 1, pp. 647-673, 1st Quart. 2018.
3. B. Chen, J. Chen, Y. Gao, and J. Zhang, “Coexistence of LTE-LAA and Wi-Fi on 5 GHz with Corresponding Deployment Scenarios: A Survey,” IEEE Commun. Surveys Tuts., vol. 19, no. 1, pp. 7-32, 1st Quart. 2017.
4. L. Simić, A. M. Voicu, P. Mähönen, M. Petrova, and J. P. De Vries, “LTE in Unlicensed Bands Is Neither Friend Nor Foe to Wi-Fi,” IEEE Access, vol. 4, pp. 6416-6426, 2016.
5. S. Lagen et al., “New Radio Beam-Based Access to Unlicensed Spectrum: Design Challenges And Solutions,” IEEE Commun. Surveys Tuts., vol. 22, no. 1, pp. 8-37, 1st Quart. 2020.
6. G. Naik, J. -M. Park, J. Ashdown, and W. Lehr, “Next Generation Wi-Fi And 5G NR-U In The 6 Ghz Bands: Opportunities And Challenges,” IEEE Access, vol. 8, pp. 153027-153056, 2020.
7. R. Zhang et al., “LTE-Unlicensed: The Future of Spectrum Aggregation For Cellular Networks,” IEEE Wirel. Commun., vol. 22, no. 3, pp. 150-159, June 2015.
8. 3GPP, “3rd Generation Partnership Project; TSG RAN; Study On Licensed Assisted Access To Unlicensed Spectrum,” 3GPP, Sophia Antipoles, France, TR 36.889, Release 13, V13.0.0, June 2015.
9. H. Kwon et al., “Licensed-Assisted Access To Unlicensed Spectrum In LTE Release 13,” IEEE Commun. Mag., vol. 55, no. 2, pp. 201-207, Feb. 2017.
10. A.-K. Ajami and H. Artail, "On The Modeling And Analysis Of Uplink And Downlink IEEE 802.11ax Wi-Fi With LTE In Unlicensed Spectrum”, IEEE Trans. Wireless Commun., vol. 16, no. 9, pp. 5779-5795, Sep. 2017.
11. M. Mehrnoush, V. Sathya, S. Roy, and M. Ghosh, “Analytical modeling of Wi-Fi and LTE-LAA coexistence: Throughput and impact of energy detection threshold”, IEEE/ACM Trans. Netw., vol. 26, no. 4, pp. 1990-2003, Aug. 2018.
12. A. D. Shoaei, M. Derakhshani, and T. Le-Ngoc, “Efficient LTE/Wi-Fi Coexistence In Unlicensed Spectrum Using Virtual Network Entity: Optimization And Performance Analysis,” IEEE Trans. Commun., vol. 66, no. 6, pp. 2617-2629, Jun. 2018.
13. S. Lagen, N. Patriciello, and L. Giupponi, “Cellular and Wi-Fi in Unlicensed Spectrum: Competition Leading To Convergence,” Proc. 2020 2nd 6G Wireless Summit (6G SUMMIT), Levi, Finland, 17-20 Mar. 2020, pp. 1-5.
14. G. Naik, and J. M. Park, “Coexistence of Wi-Fi 6E and 5G nr-u: Can we do better in the 6 GHz bands?” [online] available: https://winser.ece.vt.edu/wp-content/uploads/2020/12/ Infocom_2021_WiFi6__5G-NR-U.pdf [retrieved: August 21, 2021]
15. *Mandate to CEPT to Study Feasibility and Identify Harmonized Technical Conditions for Wireless Access Systems Including Radio Local Area Networks in the 5925–6425 MHz Band for the Provision of Wireless Broadband Services, Dec. 2017, [online] Available: http://ec.europa.eu/newsroom/dae/document.cfm?doc_id=50343. [retrieved: August 21, 2021]*
16. 3GPP, “3rd generation partnership project; TSG RAN; study on NR-based access to unlicensed spectrum,” 3GPP, Sophia Antipoles, France, TR 38.889, Release 16, V16.0.0, Dec. 2018.
17. R. Ratasuk, N. Mangalvedhe, and A. Ghosh, “LTE In Unlicensed Spectrum Using Licensed-Assisted Access,” Proc. 2014 IEEE Globecom Workshops (GC Wkshps), Austin, TX, USA, 8-12 Dec. 2014, pp. 746-751.
18. R. Kwan et al., “Fair Co-Existence Of Licensed Assisted Access LTE (LAA-LTE) and Wi-Fi In Unlicensed Spectrum,” Proc. 2015 7th Computer Science and Electronic Engineering Conference (CEEC), Colchester, UK, 24-25 Sept. 2015, pp. 13-18.
19. O. Sallent, J. Pérez-Romero, R. Ferrús, and R. Agustí, “Learning-Based Coexistence For LTE Operation In Unlicensed Bands,” Proc. 2015 IEEE International Conference on Communication Workshop (ICCW), 8-12 June 2015, pp. 2307-2313.
20. S. K. Ahmed, “Carrier Sense Adaptive Transmission (CSAT) in Unlicensed Spectrum,” US Patent No. US 9,491,632 B2, Nov. 8, 2016.
21. A. K. Sadek, T. Kadous, K. Tang, H. Lee, and M. Fan, “Extending LTE to Unlicensed Band - Merit and Coexistence,” Proc. 2015 IEEE International Conference on Communication Workshop (ICCW), London, UK, 8-12 June 2015, pp. 2344-2349.
22. R. K. Saha, “On Operating 5G New Radio Indoor Small Cells In The 60 Ghz Unlicensed Band,” unpublished, *Proc.* the Seventeenth International Conference on Wireless and Mobile Communications (ICWMC), Nice, France, 18-22 July 2021.
23. S. Chatterjee, M. J. Abdel-Rahman, and A. B. MacKenzie, “Optimal Distributed Allocation Of Almost Blank Subframes For LTE/Wifi Coexistence,” Proc. 2017 15th International Symposium On Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), Paris, France, 15-19 May 2017, pp. 1-6.
24. R. K. Saha, “A Hybrid Interweave-Underlay Countrywide Millimeter-Wave Spectrum Access And Reuse Technique For CR Indoor Small Cells In 5G/6G Era,” Sensors, vol. 20, no. 14, art. no. 3979, 2020.
25. R. K. Saha, “Millimeter-wave Spectrum Utilization Improvement In Multi-Operator Networks: A Framework Using The Equal Likelihood Criterion,” IEEE Access, vol. 9, pp. 72980-72999, 2021.
26. R. K. Saha, “Power-Domain Based Dynamic Millimeter-Wave Spectrum Access Techniques For In-Building Small Cells In Multioperator Cognitive Radio Networks Toward 6G,” Wirel. Commun. Mob. Comput., vol. 2021, art. ID 6628751, 13 pages, 2021.
27. R. K. Saha, “An Overview And Mechanism For The Coexistence Of 5G Nr-U (New Radio Unlicensed) In The Millimeter-wave spectrum for indoor small cells,” unpublished, Wirel. Commun. Mob. Comput., 2021.
28. R. K. Saha “Spectrum Allocation And Reuse In 5G New Radio On Licensed And Unlicensed Millimeter-Wave Bands In Indoor Environments,” Mob. Info. Syst. vol. 2021, art. ID 5538820, pages 21, 2021.
29. R. K. Saha, “Licensed Countrywide Full-Spectrum Allocation: A New Paradigm For Millimeter-Wave Mobile Systems In 5g/6g era,” IEEE Access, vol. 8, pp. 166612-166629, 2020.
30. N. Rastegardoost and B. Jabbari, “Statistical characterization of wifi white space,” IEEE Commun. Lett., vol. 21, no. 12, pp. 2674-2677, Dec. 2017.
31. N. Rastegardoost and B. Jabbari, “A Machine Learning Algorithm For Unlicensed LTE And Wifi Spectrum Sharing,” Proc. 2018 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN), Seoul, South Korea, 22-25 Oct. 2018, pp. 1-6.
32. M. Alsenwi et al., “Towards Coexistence Of Cellular And Wifi Networks In Unlicensed Spectrum: A Neural Networks based approach,” IEEE Access, vol. 7, pp. 110023-110034, 2019.
33. Z. Han, N. Dusit, W. Saad, T. Basar, and A. Hjørungnes, Game theory in Wireless And Communication Networks: Theory, Models, And Applications. Cambridge University Press, 2012.
34. M. Ali, S. Qaisar, M. Naeem, W. Ejaz, and N. Kvedaraite, “LTE-U WiFi Hetnets: Enabling Spectrum Sharing For 5G/Beyond 5G Systems,” IEEE Internet Things Mag., vol. 3, no. 4, pp. 60-65, Dec. 2020.
35. 3GPP, *“*3rd generation partnership project; TSG RAN; *study on licensed-assisted access to unlicensed spectrum,*” 3GPP, Sophia Antipoles, France, TR 38.889, Release 13, V13.0.0, June 2015.
36. M. Hirzallah, M. Krunz, B. Kecicioglu, and B. Hamzeh, “5G New Radio Unlicensed: Challenges And Evaluation,” IEEE Trans. Cogn. Commun. Netw., Early Access, pp. 1-1, Dec. 2020.
37. Y. Huang, Y. Chen, Y. T. Hou, W. Lou, and J. H. Reed, “Recent Advances Of LTE/WiFi Coexistence In Unlicensed Spectrum,” IEEE Netw., vol. 32, no. 2, pp. 107-113, March-April 2018.

End of the Presentation

Thank You …