3GPP: The Unlicensed Journey

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Abstract

Along the long road 3GPP has traversed towards realization of cellular technologies operating in unlicensed bands, evolutions have taken place across the wireless industry and real-world applications, shaping, and at times, altering the expectations, design goals, and foundations of the technology. This paper provides an insight into such evolutions as well as brief descriptions of the 3GPP unlicensed technologies.

Introduction

Almost a decade ago, leading mobile operators started turning their eyes to the unlicensed spectrum as a fantastic bulk of underutilized resource, merely occupied by Wi-Fi. Perhaps back then, they did not foresee a universally standardized technology operating independently in the unlicensed spectrum as a complementary competitor to Wi-Fi technology.

It was essentially the carrier aggregation feature introduced in Long Term Evolution (LTE) Release 10, which later paved the way for the 3rd generation partnership project (3GPP) standardization effort in unlicensed bands. Operators were facing an ever-increasing demand for mobile data traffic, mainly driven by high-resolution video content, device proliferation, as well as emerging applications such as internet-of-things (IoT), machine-type communications (MTC), and vehicle-to-anything communications (V2X) [1]. The wireless industry has been evolving around this situation to increase a network capacity that can meet the rapidly growing demand. New technologies, namely, massive Multiple-input multiple-output (MIMO), Millimeter Wave (mmWave), carrier aggregation, and dual connectivity, have been developed and further adopted by the operators to improve spectral efficiency. There have also been attempts towards opening new spectrum bands to address a spectrum shortage and to grow an extent of cellular service, by making large portions of bandwidth available for use across several channels. For example, the Federal Communications Commission (FCC) made an additional 500 MHz bandwidth available on a global basis in the unlicensed 5 GHz band which has been occupied only by Wi-Fi [2].

The idea of using unlicensed spectrum arose as an appealing option for boosting cellular services and offloading the excess data traffic of cellular networks. The carrier aggregation and the supplemental downlink features of LTE made it possible to offer significantly better coverage as well as higher spectral efficiency compared to Wi-Fi, while allowing seamless flow of traffic across licensed and unlicensed carriers in a single core network. For the user, this meant higher data rates along with high reliability and robust mobility through the licensed anchor carrier.

Shared Spectrum Channel Access

Interference with the well-established incumbent technology in a target unlicensed band, Wi-Fi, was a big concern since day one. In unlicensed bands, wireless devices share the spectrum. Thus, transmissions from one device can interfere and potentially collide with transmissions from other devices. To enable coexistence between Wi-Fi and cellular technologies, channel access mechanisms were desired that could determine how devices across different radio access technologies (RATs) coexist with one another. For a fair coexistence, any

RAT operating in unlicensed bands must follow regional regulatory requirements of a corresponding band.

Following are some of the technology developments for enabling coexistence of cellular networks with Wi-Fi in unlicensed bands:

- LTE-U (LTE in Unlicensed Bands): LTE-U was pioneered in the USA and other countries without a Listen-Before-Talk (LBT) regulatory, which used Carrier Sensing Adaptive Transmission (CSAT) to guarantee Wi-Fi transmission time and a fairly divided channel access time between two networks [3]. In CSAT, a duty cycle is defined, and the LTE-U cell transmits during an adaptive fraction of the cycle, dictated by a long-term sensed medium activity, and vacates the channel for the remaining duration. Although LTE-U triggered debates with the Wi-Fi community, it was ruled out from the standardization framework, mainly due to inflexibility and long latency caused by duty cycling. However, it did evolve into the standardized technologies such as License Assisted Access (LAA).

- LWA (LTE Wi-Fi Aggregation): defined by 3GPP, this technology enables utilizing both LTE and Wi-Fi links simultaneously, without requiring hardware changes to the network infrastructure equipment and mobile devices. LWA leverages carrier Wi-Fi deployments based on a dual connectivity architecture, where Wi-Fi is used instead of a secondary LTE eNB.

- LAA: extension of LTE to unlicensed spectrum based on carrier aggregation, which has been standardized by 3GPP.

- MulteFire: designed to deploy LTE in unlicensed spectrum for a stand-alone operation, MulteFire enables private LTE and neutral host deployment models with a Wi-Fi-like deployment based on LBT. MulteFire Alliance is independently developing MulteFire specifications for markets including IoT, while 3GPP has started working on extending MulteFire to 5G under New Radio (NR) in Unlicensed Spectrum (NR-U).

Technical workshops and intense cross-industry discussions started between the cellular technologies based on 3GPP standards and the independent Wi-Fi technology based on Institute of Electrical and Electronics Engineers (IEEE) standards. Harmonized standards were developed by the European Telecommunications Standards Institute's (ETSI) Broadband Radio Access Networks (BRAN)

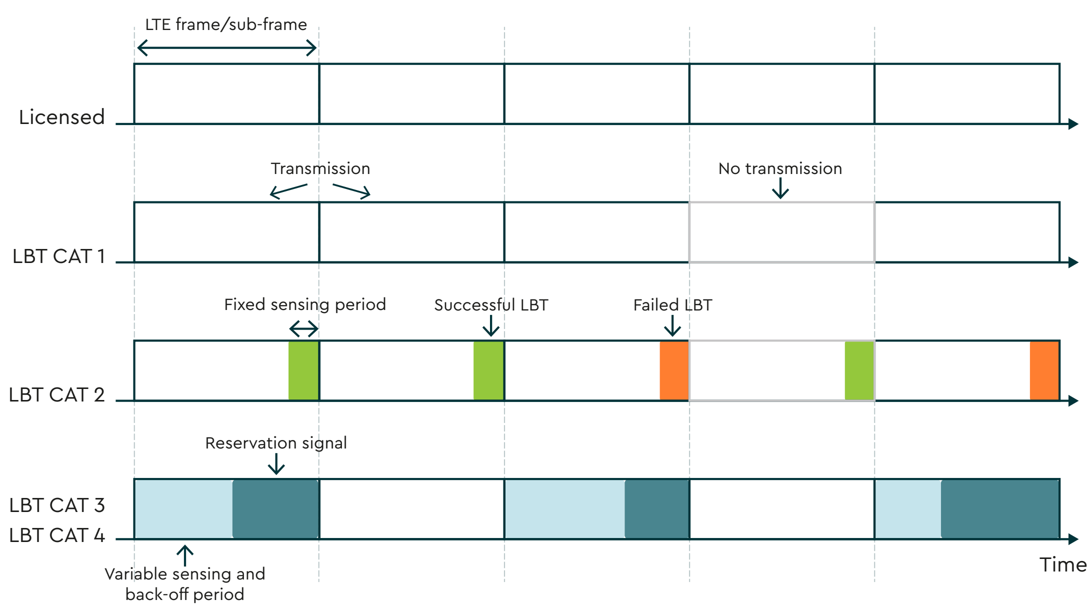

FIG. 1 Categories of LBT Procedure

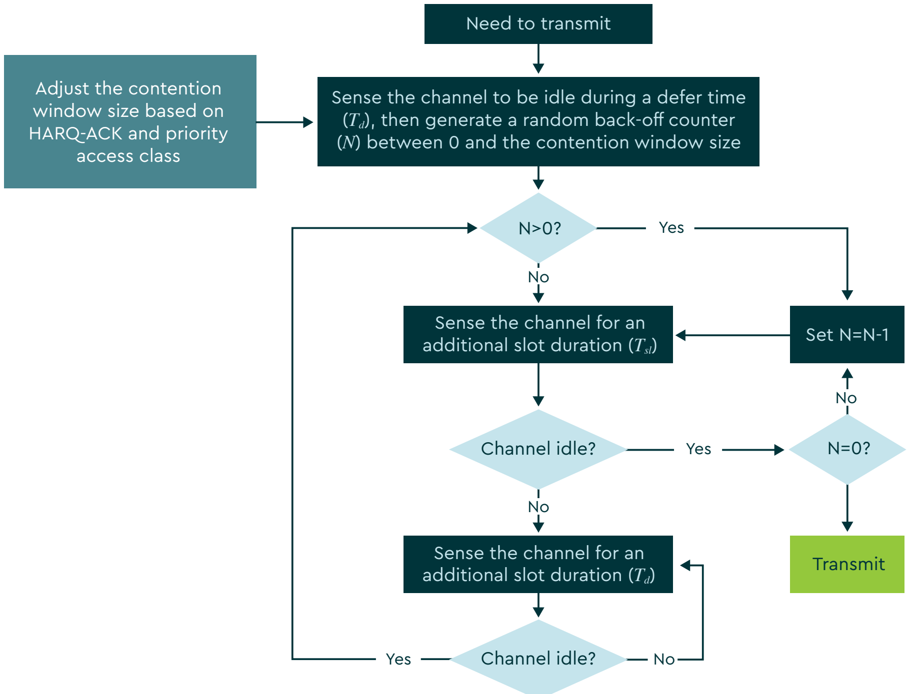

FIG. 2 LBT Category 4, where $T_d = T_f + m_p \cdot T_{sl}$, $T_f = 16\mu s$, $T_{sl} = 9\mu s$, and m_p is determined based on channel access priority class

committee, including most strict regulations. Basically, the Wi-Fi community, being after a so-called "good neighbor" and "fair coexistence", thoroughly influenced the direction and the outcomes of the discussions for 3GPP operation in an unlicensed spectrum. A fundamental design philosophy was to align the channel access mechanism of the 3GPP technologies with that of the Wi-Fi, as much as possible. This philosophy was adopted since the initial study in LTE-LAA Release 13, where a single global solution framework for licensed assisted access to the unlicensed spectrum based on a supplemental downlink was sought.

A most popular channel access mechanism in unlicensed bands, a similar concept of which is used by Wi-Fi, was LBT, working based on a concept of contention-based access. In LBT, transmitters are expected to "sense" the medium, based on a Clear Channel Assessment (CCA) protocol, and detect transmissions from other nodes prior to transmitting. The simplest CCA method is energy detection, i.e., to measure the received energy level of signals transmitted from other devices and determine whether a channel is idle or busy. This method works based on the energy emitted by a transmitter on a radio channel, regardless of the technology-related features of the transmitted signal. Different types (categories) of LBT procedure are defined; namely: LBT CAT1 which requires no sensing; LBT CAT2 with a fixed sensing period; and LBT CAT3 and LBT CAT4 with variable sensing periods and random back-offs. The wireless device can transmit if the CCA indicates that the channel is idle, otherwise, the wireless device must defer the transmission. An example of LBT deployment in LTE is illustrated in FIG. 1.

FIG. 2 shows the LBT Category 4 (CAT4 LBT) for a Load Based Equipment (LBE), with random back-off and variable contention window size. In LBE, the device can transmit on the channel whenever there is data in its buffer. The back-off time plays an important role in fairly splitting the channel time between Wi-Fi and LTE-LAA. It is worth mentioning that Wi-Fi does not implement the defer periods in the carrier sensing mechanism, instead, it performs exponential back-off of the contention window, which is not performed by LBT.

As part of the LBT procedure, Wi-Fi devices use a combination of energy detection and reception of a known modulated and encoded signal, called a preamble, transmitted by Wi-Fi devices at the beginning of the signal. In short, if a Wi-Fi preamble is detected with energy above -82 dBm in a 20 MHz channel, or if any energy is detected above -62 dBm in a 20 MHz bandwidth, the Wi-Fi device does not transmit [4]. Despite the significant effort by the Wi-Fi industry, 3GPP did not comply with the costly implementations and performance limitations of a variation of the Wi-Fi preamble or a lower energy detection threshold. Instead, in a future-committed innovation-driven decision, 3GPP adopted a single common maximum energy detection threshold of -72 dBm for all devices in favor of scalability, adaptability, forward compatibility, less complexity, robustness, and of course, fairness for cross-technology coexistence.

LAA was approved by 3GPP in LTE Release 13, based on a license-exempt downlink, where LTE is operated on an unlicensed carrier in the 5 GHz band aggregated with a primary carrier in the licensed LTE band. In Release 14, enhanced LAA (eLAA) added support for a license-exempt scheduled uplink. Release 15 further supported the license-exempt autonomous uplink in a further enhanced LAA (feLAA). In summer 2020, 3GPP Release 16 was finalized, enabling stand-alone deployment of the 5G NR in unlicensed spectrum (referred to as NR-U) in the license-exempt 5 GHz and 6 GHz bands. Based on NR-U, an NR carrier operates independently in an unlicensed spectrum.

5G in Unlicensed Spectrum

5G was designed to handle a massive increase in data traffic with the ambition to support unseen services and a broad range of new use cases, from autonomous vehicles to smart factories and agriculture. Basically, new 5G environments such as factories, eHealth, automotive, and energy are typically served by private networks, which traditionally use Wi-Fi technology. In dense environments, unlicensed technologies coupled with core networks can increase the access network capacity and improve users' experience. The wireless industry believes that 5G greatly relies on unlicensed technologies, led by Wi-Fi, which is often owned and operated by cellular operators as a complement to the licensed operation. Meanwhile, 3GPP unlicensed technologies provide an additional option with the potential to increase access opportunities, improve spectral efficiency, and enhance the end-user experience even further. It has been demonstrated that these technologies complement each other rather than compete [4], and thus, push the technological boundaries further forward and better serve the users. For instance, Wi-Fi may be mostly deployed in indoor scenarios, whereas LTE-LAA and NR-U deployments are mostly outdoors. Also, due to a higher universal energy detection threshold, Wi-Fi system's coverage is relatively limited, which can be compensated for by 3GPP technologies through their more robust coverage and higher data rates, especially on important control channels and more so when anchored to licensed carriers.

A phase 1 version of 5G NR was standardized in late 2018 under 3GPP Release 15, determined to fulfill the requirements put forth by the International Telecommunication Union (ITU): increased pick data rates for enhanced Mobile Broadband (eMBB), proliferated density of connections for massive Machine Type Communication (mMTC), and below 1 ms latency for Ultra-Reliable Low-Latency Communications (URLLC) [1]. NR phase 2 was completed in Release 16, which includes both incremental improvements to existing features, as well as features that provide new verticals and deployment scenarios. The most notable enhancements of Release 16 address MIMO and beamforming enhancements, dynamic spectrum sharing, dual connectivity, carrier aggregation, and power saving. The new features addressed in Release 16 comprise intelligent transportation systems and V2X communications, Industrial IoT (IIoT), non-terrestrial networks, high-precision positioning, mission-critical design of URLLC, and NR-U.

NR-U is primarily established as a general-purpose technology to extend the applicability of 5G NR to unlicensed spectrum. Targeting the 5 GHz and 6 GHz bands, NR-U supports both standalone and licensed-assisted operation based on carrier aggregation and dual connectivity with either NR or LTE in the licensed spectrum. The ultra-lean transmission and flexible NR frame structure of Release 15 combined with the LAA principles provide an excellent basis for the functionality of NR-U to rely on. Yet, the standalone deployment requires a redesign of initial access, channels and signals, and scheduling procedures that take into account the regulatory requirements including LBT, maximum Channel Occupancy Time (COT), Occupied Channel Bandwidth (OCB), power limits, and specific functionalities such as dynamic frequency selection and frequency reuse [5]. Based on these requirements, enhancements and modifications to Release 15 are considered, some of which are as follows [6]:

- Initial access and paging: Introduction of Discovery Reference Signal (DRS) containing at least Synchronization Signal/Physical Broadcast Channel (SS/PBCH) block burst set transmission, increasing the maximum number of candidate SS/PBCH block positions within the DRS window, and handling of reduced SS/PBCH block and Remaining Minimum System Information (RMSI) transmission opportunities due to LBT failure, flexibility in monitoring paging signals to compensate for missed transmission opportunities due to LBT.

- Random access: Modifications to the random access procedure to handle reduced message 1/2/3/4 transmission opportunities due to LBT failure such as Physical Random Access Channel (PRACH) repetition in frequency domain and extension of random access response window from 10 ms to 20 ms, extension of the PRACH preamble formats to meet the OCB requirement, introduction of a 2-step random access procedure.

- Downlink channels and signals: Dynamic monitoring of Physical Downlink Control Channel (PDCCH), flexible starting positions for Physical Downlink Shared Channel (PDSCH) due to uncertainty caused by LBT, and COT structure indication.

- Uplink channels and signals: Block interlaced based Physical Uplink Control Channel (PUCCH) and Physical Uplink Shared Channel (PUSCH) design to comply with OCB requirement, flexible starting positions for PUSCH due to LBT, additional flexibility in configuring and triggering Sounding Reference Signal (SRS).

- Hybrid Automatic Repeat Request (HARQ) operation: Additional Acknowledgement and Negative Acknowledgement (ACK/NACK) transmission opportunities, immediate transmission of ACK/NACK for corresponding data in the same shared COT as well as the subsequent COT.

- Wideband operation: Support of downlink and uplink transmissions of a bandwidth larger than that of a Wi-Fi channel (20 MHz).

- Frame structure: Single and multiple downlink to uplink and uplink to downlink switching points within a shared COT with associated identified LBT requirements.

The LBT protocol for NR-U follows that of LTE-LAA. Four LBT categories are defined for channel access procedure in NR-U [6]:

- Cat1 LBT: Immediate transmission after a short switching gap of 16 µs (no CCA).

- Cat2 LBT: LBT without random back-off, with a deterministic CCA period (e.g., 25 µs).

- Cat3 LBT: LBT with random back-off and a variable extended CCA period, randomly drawn from a fixed-sized contention window.

- Cat4 LBT: LBT with random back-off and a variable extended CCA period, randomly drawn from a variable-sized contention window, whose size can vary based on channel dynamics.

Different categories can be applied to different transmissions in a COT under certain conditions. For example, Cat4 LBT is used by the base station or the wireless device to initiate a COT for transmissions, while Cat1 is used for back to back transmissions in a burst.

NR-U allows for up to 400 MHz and 100 MHz of channel bandwidth in the downlink and uplink, respectively. NR-U offers mobility and the Quality of Service (QoS) that is expected from 5G NR. With the 5G standardized solution to reliable transparent connection of time-sensitive networks (TSNs), technologies such as multiple transmission and reception points (multi-TRP), URLLC, and IIoT can all be deployed with NR-U in controlled environments and private networks.

Unlicensed Release 17

3GPP endeavor on NR Release 17 officially started in December 2019, to further enhance the existing NR features for deployed functionalities and new requirements emerging in the market, as well as to introduce new features for mainly three use cases: eMBB, URLLC, and mMTC.

Enhancements
A work item is defined in NR Release 17 for enhanced IIoT and URLLC support, including unlicensed operation in controlled environments, where interference from other systems is not expected, and thus, possibility of LBT failure would depend on the deployment. Enhancements mainly focus on uplink URLLC, with the consideration that semi-static configurations are great options for operation in controlled environments.

One of the objectives of the work item is to harmonize uplink semi-static transmission—or configured grant— enhancements in NR-U and URLLC introduced in Release 16 to be applicable for the unlicensed spectrum [7]. Depending on the deployment scenario and potential interference characteristics, the design of configured grant in NR IIoT/URLLC (defined for licensed spectrum) or NR-U configured grant can be considered as a baseline.

Enhancements for semi-static channel occupancy (a.k.a. Frame-Based Equipment—FBE), which works based on a Fixed Frame Period (FFP), is another objective of this work item. FBE is another channel access mechanism based on LBT, in which unlicensed devices contend for the channel beginning only at synchronized frame boundaries. FBE, as opposed to LBE, might be a better option for IIoT applications. Both FBE and LBE, illustrated in FIG. 3, were supported in Rel. 16. An FFP, ranging from 1 ms to 10

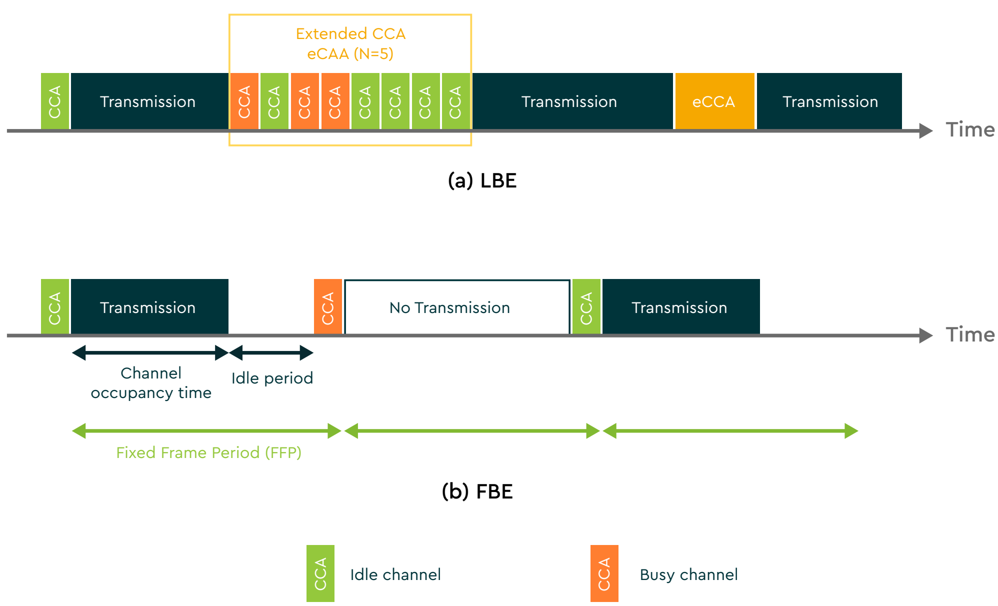

FIG. 3 (a) LBE-based channel access and (b) FBE-based ms, consists of a semi-static channel occupancy time followed by an idle period, whose duration is at least 5% of the FFP and not less than 100 µs. An initiating device performs CCA on the operating channel immediately before starting transmissions at the beginning of an FFP. If the device finds the channel occupied (LBT failure), it does not transmit on the channel during the FFP. It is desired to enable COT initiation by the wireless device with FBE operation [7].

New Features

3GPP plans to extend NR operation up to 71 GHz, and also, to unlicensed bands of 60 GHz. Extension to much higher carrier frequencies is essential due to increasing traffic and demand for higher data rates and a need for more bandwidth. One or more new and larger subcarrier spacings are to be adopted, which will impact the time-line related aspects such as: bandwidth part and beam switching times, HARQ scheduling, preparation, computation, and processing times. With the propagation characteristics of the high-frequency range, beam-based communication is especially vital.

Although NR-U procedures and protocols are to be leveraged to the extent possible, protocols are required to specify the channel access mechanism for unlicensed operation in this frequency range. 3GPP is actively discussing the channel access aspects in a study item, trying to address identified challenges. The regulations governing unlicensed portions of the 57–71 GHz band vary depending on the region. For example, the United States imposes a power limit but does not mandate a spectrum sharing mechanism. Also, LBT is not mandated in China, Japan, South Korea, and Australia. In Europe, depending on the deployment scenario, either: LBT with CCA is mandated, directional antennas are enforced, or a new spectrum access regulation is applied.

Multiple companies suggest not to mandate LBT procedure, but to provide the designs for where they are needed by regulation, or if useful, for performance enhancements. Thus, 3GPP may support both channel access mechanism with LBT and without LBT [8]. Some techniques are being considered to improve LBT, e.g., directional sensing or beam-based LBT, receiver-assisted LBT, and adaptation of sensing threshold. Additional coexistence mechanisms other than LBT are also proposed, including: Automatic Transmit Power Control (ATPC) which does not require measurement and is based on an autonomous good neighbor behavior; as well as measurement/long-term sensing-based solutions such as Dynamic Frequency Selection (DFS) and duty cycling. Moreover, a mechanism to switch in and out of LBT mode may be adopted. For a baseline LBT mechanism in the unlicensed 60 GHz band, 3GPP adopted the regulation defined for the band by ETSI Harmonized European Standard (EN) 302 567, as opposed to the NR-U LBT procedure. Enhancements on energy detection threshold and contention window size based on the sensing bandwidth may be considered. For a harmonious coexistence on the 60 GHz band, 3GPP may support a channelization mode aligned with Wi-Gig (IEEE 802.11 ad) channels of 2.16 GHz bandwidth, however, smaller bandwidths may also be supported. Similar to NR-U operation below 52.6 GHz, NR-U operation in 60 GHz can be: standalone, aggregated via carrier aggregation; or dual connectivity with an anchor carrier.

Conclusion

The evolutionary path that 3GPP has undertaken to operate in unlicensed spectrum is shown in this paper, including the challenging coexistence with the well-established Wi-Fi technology, and going from an unjustified monetizer to a complementary competitor. Harmonizing enhancements as well as the new operational features, which helped the realization of high-performance cellular networking in the unlicensed spectrum, were also introduced along with the development of 3GPP releases.

Acronym List

3GPP	3rd Generation Partnership Project
Wi-Fi	Wireless Fidelity
LTE	Long Term Evolution
IoT	Internet of Things

MTC	Machine Type Communications
V2X	Vehicle-to-Anything Communications
MIMO	Multiple Input Multiple Output
mmWave	Millimeter Wave
FCC	Federal Communications Commission
GHz	Giga Hertz
RAT	Radio Access Technologies
LTE-U	LTE in Unlicensed Bands
LBT	Listen Before Talk
CSAT	Carrier Sensing Adaptive Transmission
LAA	Licensed Assisted Access
LWA	LTE Wi-Fi Aggregation
eNB	E-UTRAN Node B
IEEE	Institute of Electrical and Electronics Engineers
ETSI	European Telecommunications Standards Institute
BRAN	Broadband Radio Access Networks
CCA	Clear Channel Assessment
dBm	Decibel-Milliwatts
MHz	Mega Hertz
eLAA	Enhanced LAA
feLAA	Further Enhances LAA
5G	5th Generation
NR	New Radio
NR-U	New Radio in Unlicensed Bands
ITU	International Telecommunication Union
eMBB	Enhanced Mobile Broadband
mMTC	Massive Machine Type Communication
URLLC	Ultra-Reliable Low-Latency Communications
IIoT	Industrial IoT
COT	Channel Occupancy Time
OCB	Occupied Channel Bandwidth
DRS	Discovery Reference Signal
SS/PBCH	Synchronization Signal/Physical Broadcast Channel
RMSI	Remaining Minimum System Information
PRACH	Physical Random Access Channel
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
SRS	Sounding Reference Signal
HARQ	Hybrid Automatic Repeat Request
ACK	Acknowledgment
NACK	Negative Acknowledgement
CAT	Category
QoS	Quality of Service
TSN	Time-Sensitive Networks
TRP	Transmission and Reception Points
FBE	Frame-Based Equipment
FFP	Fixed Frame Period
LBE	Load-Based Equipment
ATPC	Automatic Transmit Power Control
DFS	Dynamic Frequency Selection
EN	European Standard
Wi-Gig	Wireless Gigabit Alliance

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About the Author:

Nazanin joined Ofinno as a wireless specialist immediately after she received her PhD in Electrical Engineering from George Mason University in 2018. In 2015, she was as an Intern with Bell Labs, Stuttgart, Germany, contributing to beyond 100G optical transmission systems. She has 40 patent applications and about 10 published international papers, covering topics on PHY and MAC layer developments of wireless technologies and radio access protocols, with an emphasis on channel access and procedures in unlicensed spectrum, including LTE-U, 5G NR, and NR-U.

About Ofinno:

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