CHAPTER 8

Operation in Unlicensed and Shared Spectrum

The RF spectrum is divided into licensed and license-exempt/unlicensed bands. The traditional cellular communications systems used to exclusively operate in licensed spectrum. However, due to the insufficiency and cost of licensed spectrum below 6 GHz, the telecommunication industry has shifted attention to the unlicensed bands to deploy supplementary uplink/downlink carriers or standalone systems. The use of unlicensed spectrum has been increasingly considered by cellular operators as a complementary mechanism to offload traffic from licensed-band RF carriers to increase the overall system throughput. Various approaches to cellular operation in unlicensed spectrum have been investigated and trialed in the past few years. Two practical cellular technologies for communication in unlicensed spectrum, the LTE-U and the LTE-based license-assisted access (LAA), have been investigated by LTE-U Forum and 3GPP. The use of Wi-Fi as a complementary carrier to offload cellular networks was studied earlier and specified by 3GPP under LTE-Wi-Fi link aggregation (LWA) work item [12].

Operation in unlicensed spectrum is subject to various limitations and restrictions which are regional and band specific. The typical limits are in terms of total transmit power, power spectral density (PSD), carrier bandwidth, and duty cycle that each device can use. In addition, sharing protocols may also be specified in some bands to protect other systems in the band or to allow efficient sharing. As an example, dynamic frequency selection (DFS) aims to protect radar systems and listen-before-talk (LBT) allows efficient spectrum sharing by minimizing inter-user interference in unlicensed spectrum. 3GPP LTE began to explore 5 GHz unlicensed band for offloading cellular traffic in Rel-12. The non-standard LTE-U and standard LAA both use LTE technology as the baseline in unlicensed spectrum anchored on a licensed carrier to increase user throughput and system capacity. It must be noted that LTE-U can only be deployed in selected regions due to lack of LBT support whereas LTE-based LAA uses a similar LBT procedure as IEEE 802.11 systems. In addition to LTE-U and LAA, the standalone operation of LTE in the unlicensed spectrum has been considered by some operators.[1]

[1] MulteFire Alliance: https://www.multefire.org

5G NR. DOI: https://doi.org/10.1016/B978-0-08-102267-2.00008-7

The 60 GHz band has yet to attain significant large-scale industry traction although the specification for IEEE 802.11ad[2] system was finalized in 2012. The 60 GHz frequency bands have been used for wireless backhaul and indoor and outdoor point-to-point communication. The unlicensed 5 GHz spectrum provides about 500 MHz of usable bandwidth. A large number of Wi-Fi deployments based on the IEEE 802.11 are in 5 GHz band and are mainly used for broadband indoor applications. Cellular operators actively use Wi-Fi to offload traffic in dense hotspots using unlicensed spectrum; however, due to a high level of inter-cell interference, Wi-Fi-based offloading scenarios are not attractive for outdoor use cases.

Multi-antenna transmission and beamforming with large antenna arrays are some of the key features of the new radio systems, which can benefit the NR-unlicensed operation in the sense that transmission power can be reduced due to highly directional antennas. In addition, directional transmission leads to lower inter-user/inter-cell interference, which in turn improves the coexistence conditions. For typical network deployment where the elevation angle of the antenna is manually tilted to one fixed direction, the maximum antenna gain is only achieved in the tilted elevation direction while lower antenna gain is seen in other directions. When both elevation and horizontal beamforming are utilized (FD-MIMO), the maximum beamforming gain can be obtained in each direction via beam tracking procedures. Beamforming can improve the link budget and can increase signal-to-interference-plus-noise ratio (SINR) performance. Moreover, the interference between different systems in the unlicensed band can be minimized using highly directional antennas due to the significantly lower collision probability compared to the omnidirectional transmission cases. As a result, higher spatial reuse would be possible, increasing the system throughput as well as improving spectrum efficiency.

Some licensed frequency bands are designated for commercial use while others are designated for public safety. The assignment of a frequency band to a user allows the user to utilize that frequency and bandwidth for stated purposes using predefined emission parameters. Licensed spectrum allows exclusive use of certain frequencies in specific geographic locations, meaning that when someone is granted the right by a regulatory body to communicate at certain frequencies and in certain locations, everyone else is prohibited from using that frequency in that location. In contrast, in the spectrum that is designated as license-exempt or unlicensed, users can operate without a license but must comply with the regulatory constraints. For instance, the regulations limit the transmit power and the effective isotropic radiated power (EIRP) to minimize interference to other cochannel systems. The unlicensed frequency bands were originally allocated for industrial, scientific, and medical (ISM bands) applications.

[2] IEEE Standards Association: https://standards.ieee.org/findstds/standard/802.11ad-2012.html

To coexist with Wi-Fi in the unlicensed spectrum, some enhancements in the LTE and NR systems were required including a mechanism for channel sensing based on LBT, discontinuous transmission on a carrier with limited maximum transmission duration, DFS for radar avoidance in certain bands, and multi-carrier transmission across multiple unlicensed channels. The DTX and LBT have had major impacts on various aspects of LTE functionalities including downlink/uplink physical channel design, channel state information (CSI) estimation and reporting, HARQ operation, and radio resource management. In 5 GHz band, about 500 MHz of unlicensed spectrum is available for LAA use. This unlicensed band can be divided into multiple channels of 20 MHz bandwidth. The selection of LAA carrier(s) with minimal interference is the first step for an LAA node to coexist with Wi-Fi systems in the unlicensed spectrum. However, when a large number of nodes are present, interference avoidance cannot be guaranteed through channel selection, thereby, sharing carriers between different technologies is required. The carrier selection can be further performed periodically by adding or removing unlicensed carriers as required. These carriers are then configured and activated as secondary cells (SCells) for use by LAA-enabled UEs.

The 3GPP NR has initiated a study item in Rel-16 to investigate the required amendments in the Rel-15 NR to extend the operation to the unlicensed bands in sub-6 GHz and above 6 GHz. Meanwhile, the LTE track has continued to enhance the LAA and non-homogeneous LTE/Wi-Fi carrier aggregation solutions, which global operators have already started to deploy. In this chapter, we will review the general aspects and use cases of the operation in unlicensed spectrum including identifying the unlicensed frequency bands, overview of IEEE 802.11 operation, which is important for understanding the coexistence studies, as well as the necessary NR and LTE enhancements to address the unlicensed band operation from various aspects, including network architecture, radio access protocol structure, and L1/L2 processing, as well as deployment and implementation considerations.

8.1 General Aspects and Use Cases

8.1.1 Unlicensed and Shared Spectrum

Unlicensed/license-exempt bands are a spectrum that has been defined for use collectively by an undetermined number of independent users without registration or individual permission. For unlicensed bands, the regulatory bodies establish rules for how applications, technologies, and industries must use the spectrum that allows applications and users to coexist with limited interference to each other. The rules are defined openly with no limitation on technologies and applications other than requirements to avoid/reduce destructive interference. With unlicensed spectrum, there is no process for establishing the right of use, and therefore the band may be utilized by any device that is compliant with usage rules such as maximum power levels, bandwidth limitations, and duty cycles. The use of unlicensed spectrum is an important complement for all 5G systems and deployments, particularly in small cell deployments. Table 8.1 provides a summary of such rules for 5 GHz band utilization across the world [9,13,15,21].

In recent years, short-range communication technologies such as Bluetooth,[3] ZigBee,[4] and Wi-Fi[5] have utilized unlicensed bands for short-range communication services. The frequency mapping of unlicensed bands is country dependent, which determines the type of technology used within designated parts of the spectrum. Despite the original intent, radio communications in the ISM bands are possible as long as the communication systems are designed to tolerate the inter-user interference as well as the cochannel interference potentially from other communication systems operating in the same band. Since the advent of mobile devices, more and more short-range, low-power, low-cost wireless communication systems, such as cordless phones, Wi-Fi, Bluetooth, and ZigBee, have utilized some of the unlicensed bands in 902−928 MHz, 2.40−2.4835 GHz, and 5.725−5.875 GHz. The growing number of wireless applications in the ISM bands has motivated the wireless industry to increase the amount of spectrum available for unlicensed use. In the United States, the Federal Communications Commission (FCC) made 300 MHz of spectrum available in 5.15−5.25 GHz (UNII-1), 5.25−5.35 GHz (UNII-2A), including 5.725−5.825 GHz (UNII-3), for use by a new category of unlicensed equipment. The latter band is partially overlapped with the ISM band (5.725−5.875 GHz), hence, is sometimes referred to as Unlicensed National Information Infrastructure (U-NII)/ISM. The FCC further made available additional 255 MHz spectrum in 5.47−5.725 MHz (UNII-2C) band. This aligns the U-NII frequency band in the United States with other parts of the world, thereby allowing the same product to be used in most parts of the world. The frequency ranges 5.250−5.350 and 5.470−5.725 GHz in U-NII-2 are used by radar systems worldwide; thus the use of these bands requires DFS techniques to avoid adverse effects on radar operation [20]. In certain geographical regions, such as the European Union and Japan, support of LBT rule is mandatory to reduce the interference to other users operating in the same band. The LBT medium access rule prevents a transmitter from continuous transmission and dominating the communication channel, rather it requires the transmitter to check for other radio activities in the channel prior to transmission.

In the United States, the use of 5 GHz unlicensed spectrum is subject to FCC regulations. At present, unlicensed wireless systems can access bands 5.15−5.25 GHz (UNII-1), 5.25−5.35 GHz (UNII-2A), 5.47−5.725 GHz (UNII-2C), and 5.725−5.85 GHz (UNII-3). In addition, bands 5.35−5.47 GHz (UNII-2B) and 5.85−5.925 GHz (UNII-4) are also being

[3] Bluetooth Special Interest Group: https://www.bluetooth.com/
[4] ZigBee Alliance: https://www.zigbee.org/
[5] Wi-Fi Alliance: https://www.wi-fi.org/

Table 8.1: 5 GHz unlicensed band designations worldwide [18].

Region (Total Bandwidth)	5 GHz								
	UNII-1 100 MHz	UNII-2A 100 MHz	UNII-2B 120 MHz	UNII-2C 255 MHz			UNII-3 125 MHz		UNII-4 75 MHz
	5.15–5.25 GHz	5.25–5.35 GHz	5.35–5.47 GHz	5.47–5.59 GHz	5.59–5.65 GHz	5.65–5.725 GHz	5.725–5.825 GHz	5.82–5.85 GHz	5.85–5.925 GHz
China (325 MHz)	Indoor	Indoor DFS/TPC					Indoor/outdoor DFS/TPC		
Europe (455 MHz)	Indoor LBT	Indoor/outdoor DFS/TPC LBT		Indoor/outdoor DFS/TPC LBT					
Japan (455 MHz)	Indoor LBT	Indoor/outdoor DFS/TPC LBT		Indoor/outdoor DFS/TPC LBT					
Korea (480 MHz)	Indoor	Indoor/outdoor DFS/TPC		Indoor/outdoor DFS/TPC			Indoor/outdoor		
The United States (580 MHz)	Indoor/outdoor	Indoor/outdoor DFS/TPC		Indoor/outdoor DFS/TPC			Indoor/outdoor		

considered for unlicensed use. The FCC has some regulations regarding transmission bandwidth, maximum transmit power, out-of-band emission, power spectrum density, transmit power control (TPC), and DFS for each unlicensed band. For example, the maximum transmit power is 24 dBm in the UNII-1 and UNII-2A bands, and 30 dBm in the UNII-2C and UNII-3 bands. In addition to the maximum transmit power, TPC may further limit the output power of a transmitter to minimize interference to users of other wireless technologies. In fact, TPC is required for both the UNII-2A and UNII-2C bands. The DFS is used for unlicensed devices to detect radar signals and to change their operating channels whenever radar activity is detected. The DFS should be adopted in the UNII-2A and UNII-2C bands to protect radar signals.

Unlike LTE-based LAA/eLAA that only provide support for the 5 GHz unlicensed band, the NR is required to cover a wide range of unlicensed and shared licensed frequency bands, where regulatory and inter-RAT coexistence requirements may differ for each band. This includes 3.5 GHz band that has been designated as a shared band in the United States as well as the 5 and 60 GHz bands that are unlicensed bands. Moreover, the system design needs to consider the vastly different wireless channel characteristics for the lower carrier frequency bands such as sub-6 GHz as well as higher carrier frequency bands such as 60 GHz [26].

5G networks are expected to operate over a wide range of licensed and unlicensed frequencies in low, medium, and high spectrum bands, but some of those frequencies are yet to be specifically defined by 3GPP and ITU-R. It can be assumed that most of the bands currently being used for 4G networks will be ultimately re-allocated to 5G technologies. Meanwhile, worldwide activities have already begun to explore a number of bands between 24.25 and 86 GHz that are being studied for the 2019 World Radiocommunication Conference (WRC), as well as on bands not included in the WRC agenda item. In the United States, the FCC is planning to make 64−71 GHz band available for unlicensed use based on the same rules applicable to the unlicensed 57−64 GHz band. In addition, FCC is studying several other bands in 24 GHz and above. It further plans to make some bands available for unlicensed applications using the same rules applicable to the unlicensed 57−64 GHz band. However, it has been asked to reconsider allocating the entire 64−71 GHz band to unlicensed operations. 3GPP also has a study item on 5G in unlicensed bands below and above 6 GHz. Unlicensed bands above 52.6 GHz covering the FCC 64−71 GHz frequency range will be considered to the extent that waveform design principles remain unchanged relative to that in below 52.6 GHz bands. The FCC has allowed access to spectrum for next-generation wireless broadband in the 28 GHz (27.5−28.35 GHz), 37 GHz (37−38.6 GHz), and 39 GHz (38.6−40 GHz) bands, as well as an unlicensed band at 64−71 GHz. The new rules make available almost 11 GHz of spectrum consisting of 3.85 GHz of the licensed spectrum and 7 GHz of the unlicensed spectrum [31]. As shown in Fig. 8.1, 60 GHz unlicensed spectrum comprises up to four non-overlapping channels, where each channel has a

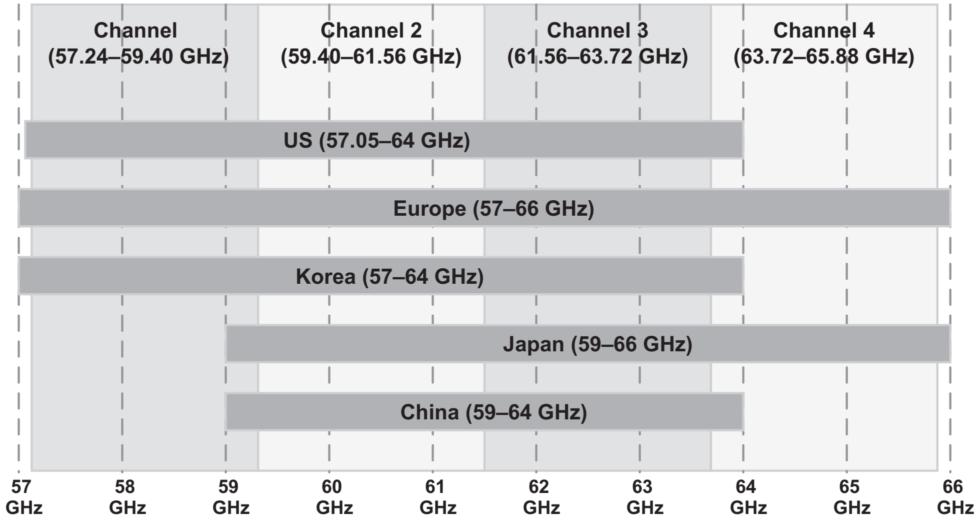

Figure 8.1
Worldwide 60 GHz unlicensed spectrum allocation [26].

bandwidth of 2.16 GHz and enables four channels in Europe; three channels in the United States, Canada, South Korea, and Japan, and two channels in China. The requirements and regulations concerning the EIRP for 60 GHz vary by geographic areas and are different from the ones in 5 GHz. For example, the requirement for peak EIRP is 43 dBm in the United States and 40 dBm in Europe where the maximum PSD is also required to be 13 dBm/MHz. The main challenge of operation in 60 GHz band is excessive path loss and blockage relative to operation in 5 GHz band. However, the large propagation loss at 60 GHz can be mitigated by increasing the antenna array gain obtained by large array sizes. Fig. 8.1 summarizes the worldwide availability and channelization of 60 GHz spectrum.

The US FCC established Citizen Broadband Radio Service (CBRS) for shared commercial use of the 3.5 GHz (3550−3700 MHz) band with the incumbent military radars and fixed satellite stations in 2015. Dynamic spectrum sharing rules have been defined to make additional spectrum available for flexible wireless broadband use while ensuring interference protection and uninterrupted use by the incumbent users. Under the plan, a three-tier sharing framework coordinates spectrum access among the incumbent military radars and satellite ground stations and new commercial users. The three tiers are as follows: incumbent, priority access license (PAL), and general authorized access (GAA) users, as shown in Fig. 8.2.

The incumbent military radar systems, satellite ground stations, and wireless ISPs are always protected from possible interference from the lower-tier PAL and GAA users. Tier-2 PAL users have the next highest priority access and are protected from GAA users.

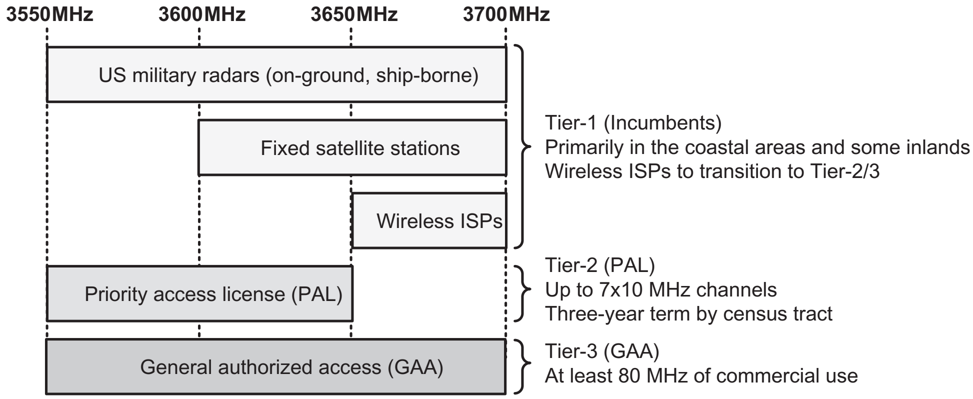

Figure 8.2
CBRS three-tier shared spectrum licensing structure [19].

PAL licenses within the 3550–3650 MHz portion of the band are assigned based on spectrum auctions. Each PAL license covers a 10 MHz channel for a single census tract (i.e., a small, relatively permanent statistical subdivision of a county) for a 3-year term. For any given census tract, up to seven total PALs may be assigned. With over 50,000 census tracts in the United States, each PAL spectrum license is expected to cost much less and encourage participation from a variety of participants. It should be noted that a PAL frequency range may change over time based on incumbent activity. The lowest-tier GAA users are permitted to use any portion of the 3.5 GHz band not assigned to higher-tier users. With an open-access rule, GAA provides free access to the spectrum similar to unlicensed spectrum. Because PAL licenses are limited to a maximum of 70 MHz in any given census tract, a minimum of 80 MHz bandwidth is available for GAA use when not in use by the incumbent users. While GAA operation does not require a costly license, GAA operators must coordinate their use of the spectrum through the dynamic spectrum sharing system [19].

As shown in Fig. 8.3, a key element of the CBRS spectrum sharing architecture is the spectrum access system (SAS). A SAS maintains a database of all CBRS base stations, also known as CBRS devices (CBSDs), including their tier status, geographical location, and other pertinent information to coordinate channel assignments and manage potential interferences. To mitigate possible interference to tier-1 military radar systems, environmental sensors known as environmental sensing capability (ESC) will be deployed in strategic locations near naval stations, mostly along coastal regions, to detect incumbent activities. When incumbent use is detected, the ESC alerts the SAS, which then directs CBSDs utilizing impacted CBRS channels in that area to move to other channels. The cloud-based SAS enforces the three-tier spectrum sharing mechanism based on FCC rules via centralized, dynamic coordination of spectrum channel assignments across all CBRS base stations in a region. The CBRS rule-making defines two classes of base stations: class-A and class-B. A

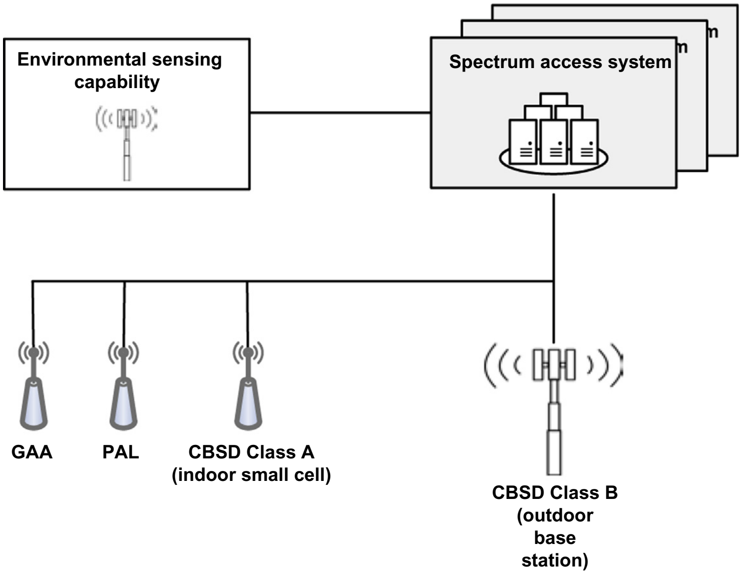

Figure 8.3
CBRS network architecture [19].

class-A base station can be an indoor or low-power outdoor small cell with a maximum conducted power of 24 dBm (per 10 MHz) and a maximum EIRP of 30 dBm. This type of small cell is similar to commercial enterprise-class small cells with 250 mW transmit power and a typical 2 dBi omnidirectional antenna or up to 6 dBi directional antenna. The class-B base station is meant for outdoor use with a maximum EIRP of 47 dBm. The highly directional antenna makes the outdoor CBRS base stations more suitable for fixed wireless use cases. While indoor and outdoor base stations can be assigned to either GAA or PAL, more indoor GAA deployments are expected until ESC certification and PAL auctions are concluded [19].

8.1.2 Use Cases and Deployment Models

The introduction of carrier aggregation in LTE-advanced required the distinction between a primary cell (PCell) and SCell. The PCell is the main cell with which a UE communicates and maintains its connection with the network. One or more SCells can be allocated to and activated for the UEs supporting carrier aggregation for bandwidth extension. Because the unlicensed carrier is shared by multiple systems, it can never match the licensed carrier in terms of mobility, reliability, and quality of service (QoS). Hence, in LAA, the unlicensed carrier is considered only as a supplemental downlink or uplink SCell assisted by a licensed PCell via carrier aggregation. LAA deployment scenarios encompass scenarios with and without macro-coverage, both outdoor and indoor small cell deployments, and both co-located and non-co-located (with ideal backhaul) cells operating in licensed and unlicensed carriers.

The LAA is based on carrier aggregation operation in which one or more low-power SCells operate in the unlicensed spectrum. Fig. 8.4 shows the prominent LAA deployment scenarios, where there are one or more licensed and unlicensed carriers. Although the backhaul for the small cells can be ideal or non-ideal, the unlicensed small cell only operates in the

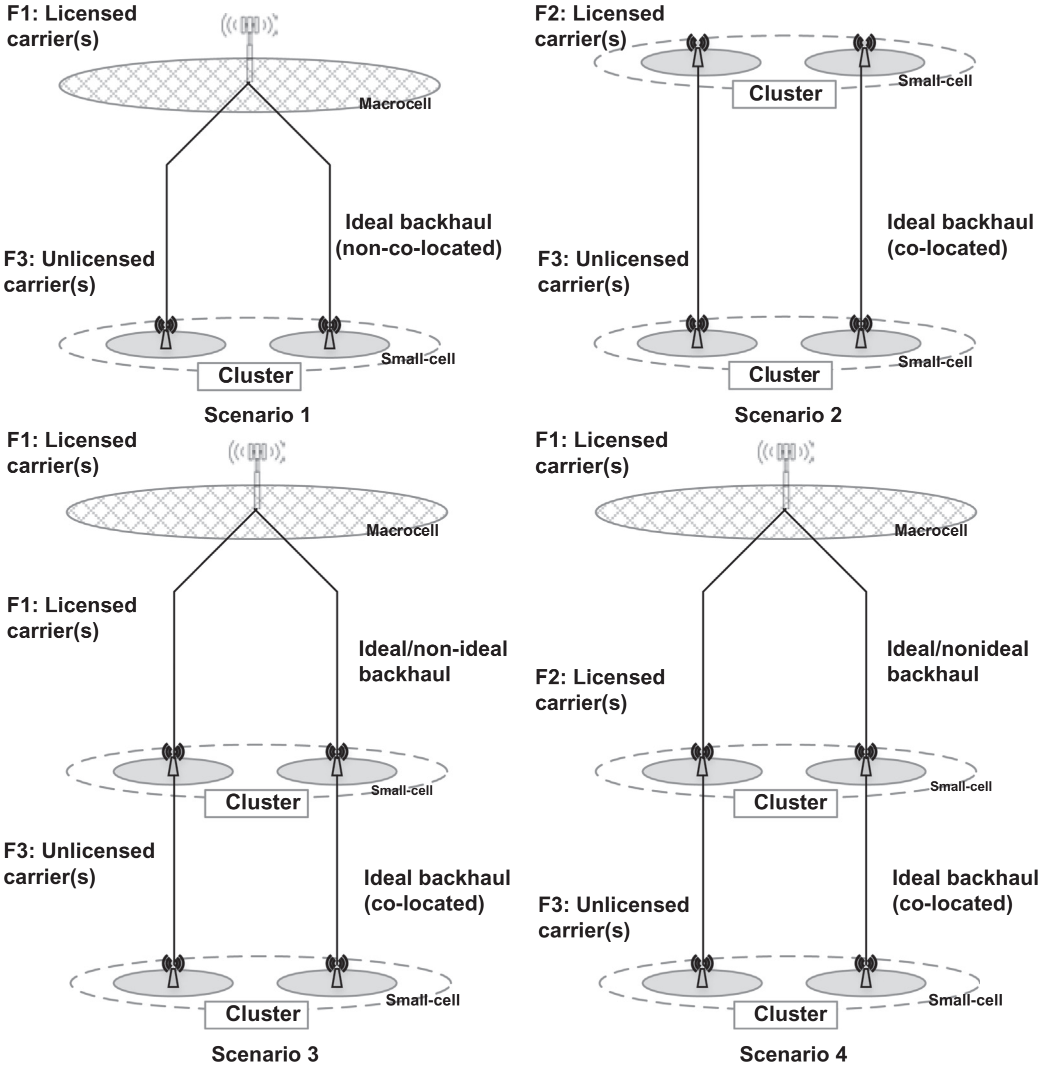

Figure 8.4
LAA deployment scenarios [12].

context of the carrier aggregation through ideal backhaul with a licensed cell. In scenarios where carrier aggregation is used within the small cell with carriers in both licensed and unlicensed bands, the backhaul between macrocell and small cell can be ideal or non-ideal.

The deployment scenarios depicted in Fig. 8.4 can be described as follows. In scenario 1, carrier aggregation between licensed macrocell (F1) and unlicensed small cell (F3) is used, whereas in scenario 2, carrier aggregation between licensed small cell (F2) and unlicensed small cell (F3) without macrocell coverage is intended. In scenario 3, licensed macrocell and small cell (F1) with carrier aggregation between licensed small cell (F1) and unlicensed small cell (F3) is utilized, and in scenario 4, licensed macrocell (F1), licensed small cell (F2), and unlicensed small cell (F3) and further carrier aggregation between licensed small cell (F2) and unlicensed small cell (F3) is used. In the latter scenario, if there is ideal backhaul between macrocell and small cell, there can be carrier aggregation between macrocell (F1), licensed small cell (F2), and unlicensed small cell (F3). If dual connectivity is enabled, there can be dual connectivity between macrocell and small cell. In the study to support deployment in the unlicensed spectrum for the above scenarios, carrier aggregation functionalities are used as a baseline to aggregate PCell/PSCell[6] on a licensed carrier and SCell on an unlicensed carrier. When non-ideal backhaul is applied between a macrocell and a small cell cluster in scenarios 3 and 4, a small cell on an unlicensed carrier must be aggregated with a small cell on a licensed carrier in the small cell cluster through ideal backhaul.

The NR-unlicensed (NR-U) study item has considered different unlicensed bands or shared bands such as 2.4, 3.5, 5, 6, 37, and 60 GHz band. Some bands are available globally whereas others are only regionally available. The NR-U study item does not target sub-gigahertz unlicensed bands due to the lack of sufficient spectrum to support efficient NR-U operation. Five deployment scenarios have been identified for NR-U as follows [12]:

- Scenario A: Carrier aggregation between licensed-band NR (PCell) and NR-U (SCell)
    - NR-U SCell may have both downlink and uplink or only downlink coverage
- Scenario B: Dual connectivity between licensed-band LTE (PCell) and NR-U (PSCell)
- Scenario C: Standalone NR-U
- Scenario D: An NR cell with a downlink in an unlicensed band and uplink in a licensed band

[6] In LTE Rel-10 and Rel-11 carrier aggregation, PUCCH was configured only on the PCell. Therefore, uplink control information, that is, HARQ ACK/NACK, CSI of SCells were transmitted on PUCCH of the PCell, if not multiplexed with SCell's own PUSCH. In LTE dual connectivity, it was determined not suitable to carry UCIs of SeNB in PUCCH of PCell in MeNB due to backhaul latency. Therefore, PUCCH is configured on a special SCell of SeNB called Primary SCell or PSCell. The PSCell is never deactivated and RACH procedure needs to be initiated upon its initial configuration.

- Scenario E: Dual connectivity between licensed-band NR (PCell) and NR-U (PSCell)

The references to sub-7 GHz bands are intended to include unlicensed bands in 6 GHz region that are under consideration by some regulatory bodies. NR-U is trying to identify additional functionalities that may need a new physical layer design (except channel access procedures) for operation in the unlicensed spectrum that are applicable to a particular frequency range (e.g., sub-7 GHz, 7−52.6 GHz, above 52.6 GHz). Optimizations for some frequency bands may be necessary due to different requirements for each band such as PSD limitation or occupied channel bandwidth (OCB), defined as the bandwidth containing 99% of the signal power, which falls between 80% and 100% of the nominal channel bandwidth. Channel bandwidths below 5 MHz are not included in this study. The study further targets the design of channel access procedures for frequency bands based on coexistence and regulatory considerations applicable to the band. The study includes identification of procedures for technology-neutral channel access for frequency bands that may become available subject to new regulations. If the absence of a Wi-Fi system cannot be guaranteed in sub-7 GHz band where NR-U is operating, the baseline assumption is that NR-U operating bandwidth is an integer multiple of 20 MHz. The following physical layer procedures may be impacted as a result of the study for NR-U: HARQ operation; configured grant support in NR-U; and channel access mechanisms. For the latter, LTE-based LAA LBT mechanism is used as the baseline. The study may further encompass enhancement of the baseline LBT mechanism; techniques to cope with directional antennas/transmissions; receiver-assisted LBT; on-demand receiver-assisted LBT, for example, receiver-assisted LBT enabled only when needed; and techniques to enhance spatial reuse, preamble detection, and enhancements to baseline LBT mechanism above 7 GHz.

The citizens broadband radio service can potentially lower the barrier to entry for non-traditional wireless carriers. The limited propagation characteristics of the 3.5 GHz spectrum facilitate indoor and floor-by-floor deployment options that could compete with the existing Wi-Fi networks. Due to the significantly lower cost of PALs compared to licensed spectrum costs, private operators now have access to 150 MHz of spectrum on every floor. This may allow enterprise applications, industrial Internet of things, and densely populated venues. Trials are already happening in the industrial IoT and smart home areas. PALs fit the need for local connectivity in remote or temporary locations for industrial complexes such as mines, power plants, oil platforms, factories, and warehouses. Private and localized LTE deployments combine the QoS of LTE and the low cost of unlicensed spectrum. Aside from industrial IoT players and general network operators looking for more available bandwidth, the SAS model for CBRS encourages more players to participate in the eventual deployment of 5G technology. Low license fees and neutral hosts allow non-traditional cellular carriers to build private networks independent of exclusively licensed frequencies or heavily congested unlicensed spectrum in 5 GHz band.

8.1.3 Principles of IEEE 802.11 Operation

IEEE 802.11 family of standards is a group of wireless local area network radio access technologies developed by IEEE 802 LAN/MAN Standards Committee. These standards define non-synchronous contention-based multiple access schemes based on carrier sense multiple access with collision avoidance (CSMA/CA). Unlike LTE, Wi-Fi takes a decentralized approach to initiate transmissions from different devices. The rule is to listen before you talk, and if your transmission collides with another transmission, wait a random period before you try again. Therefore, when a Wi-Fi device wants to begin a transmission, it senses the medium and performs a clear channel assessment (CCA). If the channel is detected to be free for a time duration referred to as distributed interframe space, or DIFS, the transmission proceeds. Otherwise, the Wi-Fi device draws a random number, between 0 and 16 (or between 0 and 32 for IEEE 802.11b/g), starts a counter and backs-off from transmission while the channel is busy. When the counter reaches zero, the device that was attempting to transmit starts transmission over the channel. However, if other devices were also sensing the carrier at the same time and tried to transmit, a collision may occur. When a transmission fails (which is detected by the absence of an ACK from the receiver), a random backoff number is drawn and the process repeats. With every backoff, the random counter value is doubled, that is, increasing as 16, 32, 64, etc. This random-access process, referred to as CSMA/CA, is illustrated in Fig. 8.5.

Most wireless systems operating in unlicensed spectrum employ CSMA as the basis for channel access. In this case, the most commonly used medium access mechanism is distributed coordination function (DCF), which is based on CSMA/CA. The DCF concept is illustrated in Fig. 8.5. A transmitting node senses the channel, and if the channel is idle for a certain time duration, that is, the DCF interframe space (DIFS), the node starts to transmit; otherwise, it continues to monitor the channel until it becomes idle for a time duration equal to DIFS. At this time, the node generates a random backoff timer, uniformly distributed within a contention window (CW). The random backoff helps avoid potential collisions, which may happen when two or more nodes are simultaneously waiting for the channel to be cleared. The backoff timer is decremented as long as the channel is idle but remains frozen when a transmission is detected and is reactivated after the DIFS period of time as soon as the channel is free. A node refrains from transmission until its backoff timer expires. Note that the DCF mechanism tries to ensure that only one transmission is present in a channel at any time, and each node has a fair share of the channel. The channel use for each node at a particular time is not guaranteed. Thus there is no deterministic schedule for transmission, reflecting the random and contentious nature of communication in the unlicensed spectrum. Reliable services and efficient resource usage are typically hard to achieve in unlicensed operation. This property is very different from that of operation in a licensed spectrum.

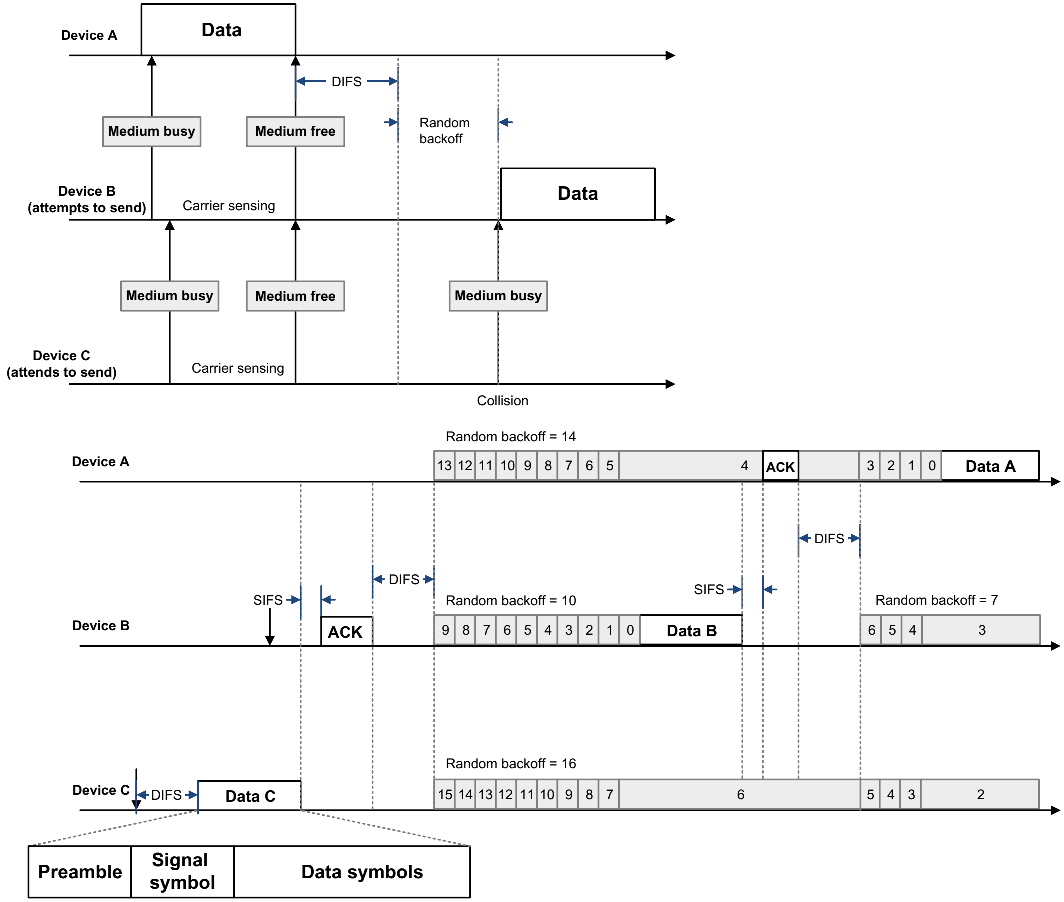

Figure 8.5
Illustration of the asynchronous Wi-Fi channel access concept [30].

A generic IEEE 802.11 frame structure consists of a set of preambles (new and legacy preambles), a signal field, and multiple data symbols. The preamble is a special waveform designed for signal identification, AGC adjustment, timing and frequency synchronization, and channel estimation. The preamble is particularly suited for activity detection in a channel because waveform detection is 10−20 dB more sensitive than the energy-detection-based CCA. Furthermore, because the IEEE 802.11 frame structure does not have a fixed timing, the preamble detection is crucial for a receiver to synchronize to the incoming frame. The signal symbol following the preamble contains information that includes the modulation and coding scheme and the total number of octets for the following data symbols that carry a MAC PDU. Depending on the payload, the frame can be very short (e.g., ACK frame) or long in the case of data frame for user traffic. Each IEEE 802.11 MAC PDU contains a transmission duration field for informing the neighboring nodes of the medium occupancy time of the current burst. This is the amount of time that all nodes must wait, if they receive it. A local timer, called a network allocation vector (NAV), of a neighboring node is updated after the node reads the duration value from the ongoing transmission. This node avoids medium access until the NAV counter expires. Using this virtual medium sensing mechanism, Wi-Fi utilizes a special clear-to-send (CTS)-to-self message to deal with the newer versions of Wi-Fi frames coexisting with a legacy node. CTS-to-self is a standard Wi-Fi CTS message except that it is addressed to the transmitting node itself, as the name implies. Nevertheless, it is meant for the neighboring nodes, if it is detected. A new generation Wi-Fi node transmits a CTS-to-self frame immediately before transmitting. The duration field of the CTS-to-self packet contains the time of the following traffic frame, thereby providing more effective protection of the subsequent frame than relying on physical medium sensing.

IEEE 802.11 supports two network architecture types namely infrastructure and ad-hoc modes. The basic service set (BSS) is the basic building block of an IEEE 802.11 network. Direct association of stations in ad-hoc network forms an independent BSS or IBSS. The interconnection of a number of BSS through a distributed system creates an extended service set. IEEE 802.11 specifications define multiple physical layers and a common MAC layer for wireless local area networks (as shown in Fig. 8.6). Another important aspect of this family is that they use unlicensed spectrum in 2.4, 5, and 60 GHz for operation.

The IEEE 802.11 family comprises many technologies that have evolved from direct sequence spread spectrum (DSSS) and complementary code keying (CCK) in the first generation to OFDM waveforms combined with advanced coding and modulation techniques and spatial division multiplexing (SDM) multi-antenna schemes in the latest generations that, depending on channel conditions, can provide data rates in the excess of a few gigabits per second within short distances. Table 8.2 summarizes the key physical layer characteristics of IEEE 802.11 air-interface technologies. There are other IEEE 802.11 family members that each provides an extension to the baseline standard by adding new features such as handover and roaming, mesh networking, QoS, security, regulatory, and measurement for various regions of the world [30].

In IEEE 802.11, the stations and the access point are not synchronized except when they exchange data or control information in the downlink or uplink. An LBT method combined with CSMA/CA is used to gain access to the medium and to ensure collision avoidance with other contenders wishing to access the shared medium. The stations either passively scan the beacons transmitted by nearby access points or actively scan neighboring access points by transmitting a probe signal.

In IEEE 802.11, there are two options for medium access. The first is a centralized control scheme that is referred to as point coordination function (PCF), and the second is a contention-based approach known as DCF. The PCF mode supports time-sensitive traffic

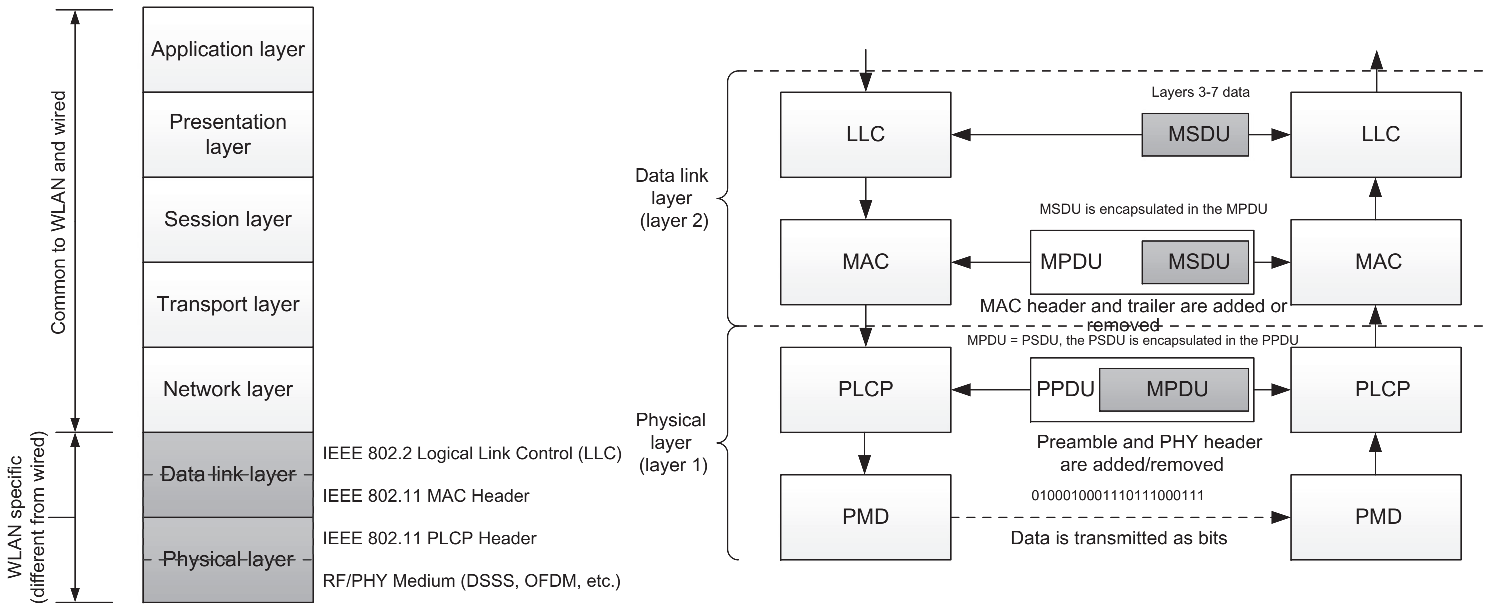

Figure 8.6
OSI and IEEE 802.11 protocol relationships [30].

Table 8.2: **Evolution of IEEE 802.11 air-interface technologies [30].**

Standard	Frequency (GHz)	Bandwidth (MHz)	Transmission Scheme	Highest Order Modulation	Coding Rate	Spatial Streams	Peak Data Rate (Mbps)
802.11	2.4	25	DSSS	–	Convolutional coding with coding rates 1/2, 2/3, 3/4, and 5/6	1	1, 2
802.11b	2.4	25	DSSS/CCK	–		1	1–11
802.11a	5	20	OFDM	64QAM		1	6–54
802.11g	2.4	25	OFDM, DSSS/CCK	64QAM		1	1–54
802.11n	2.4 and 5	20, 40	OFDM/SDM	64QAM		1–4	6.5–600
802.11ac	5	20, 40, 80, 160	OFDM/SDM/ MU-MIMO	256QAM		1–8	433 (80 MHz and one spatial stream) 6933 (160 MHz and 8 spatial streams)
802.11ad	60	2160	OFDM	256QAM		1	Up to 6912
802.11ax	2.4 and 5	20, 40, 80, 160	OFDMA/ SDM/MU-MIMO	1024QAM	Convolutional coding and LDPC with coding rates 1/2, 2/3, 3/4, and 5/6	1–8	600.4 (80 MHz and one spatial stream) 9607.8 (160 MHz and 8 spatial streams)

flows where the access points periodically send beacon frames to communicate network management and identification, which is specific to that Wi-Fi node. Between the sending of these frames, PCF splits the timeframe into a contention-free period and a contention period. If PCF is enabled on the remote station, it can transmit data during the contention-free polling periods. However, the main reason why this approach has not been widely adopted is because the transmission times are not predictable. The other approach, DCF, relies on the CSMA/CA scheme to send/receive data. Within this scheme, the MAC layer sends instructions for the receiver to look for other stations' transmissions. If it sees none, then it sends its packet after a given interval and waits for an acknowledgment. If one is not received, then it knows its packet was not successfully delivered. The station then waits for a given time interval and checks the channel before retrying to send its data packet. This can be achieved because every packet that is transmitted includes a value indicating the length of time that transmitting station expects to occupy the channel. This is noted by any station that receives the signal, and only when this time has expired other stations consider transmitting. Once the channel appears to be idle, the prospective transmitting station must wait for a period equal to the DCF interframe spacing. If the channel has been active, it must first wait for a time consisting of the DIFS plus a random number of backoff slot times. This is to ensure that, if two stations are waiting to transmit, then they do not transmit together, and then repeatedly transmit together. A time known as contention window is used for this purpose. This is a random number of backoff slots. If a transmitter intending to transmit senses that the channel becomes active, it must wait until the channel becomes free. If the channel is still busy, the transmitter continues waiting a random period for the channel to become free, but this time allowing a longer CW (see Fig. 8.7). While the system works well in preventing stations to transmit together, the result of using this access system is that, if the network usage level is high, then the time that it takes for data to be successfully transferred increases. This results in the system appearing to become slower for the users. In view of this, Wi-Fi may not provide a suitable QoS in its current form for systems where real-time data transfer is required.

To introduce QoS, a new MAC layer was developed as part IEEE 802.11e. The user traffic is assigned a priority level prior to transmission. There are eight user priority levels. The transmitter prioritizes the data by assigning one of the four access categories. The QoS-enabled MAC layer has combined features from the DCF and PCF schemes into hybrid coordination function (HCF). In this approach, the modified elements of the DCF are termed the enhanced distributed channel access (EDCA), whereas the elements of the PCF are termed the HCF controlled channel access. A new class of interframe space called an arbitration interframe space (AIFS) has been introduced for EDCA. This is chosen such that the higher the priority the message, the shorter the AIFS and associated with this there is also a shorter CW. The transmitter then gains access to the channel in the normal manner, but in view of the shorter AIFS and shorter CW, the higher the chance of it gaining access

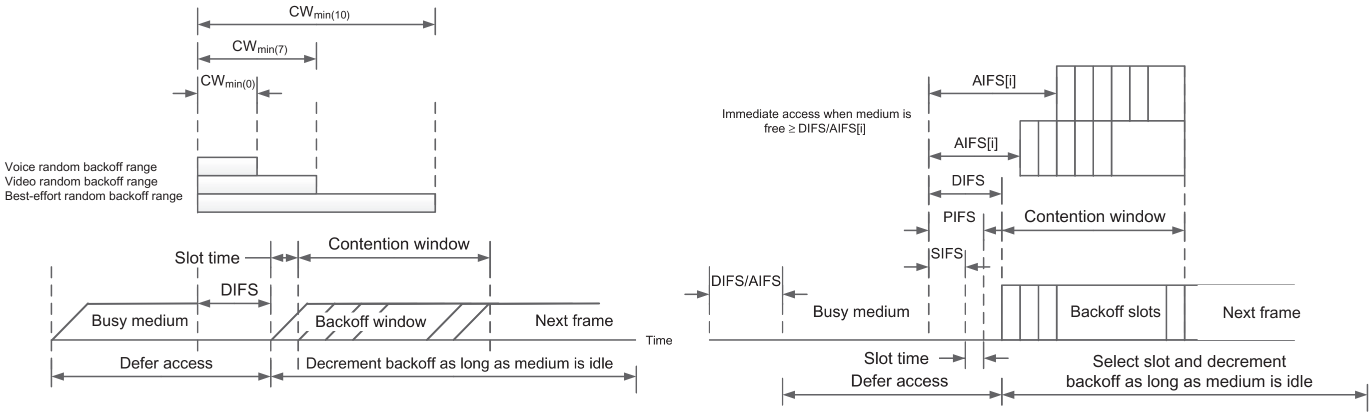

Figure 8.7
Medium access methods in IEEE 802.11 [30].

to the channel. Although statistically a higher priority message will usually gain the channel, this will not always be the case.

IEEE 802.11 frame contains a MAC header, a variable length frame body (0−2304 bytes) and 32-bit frame check sequence. The MAC header contains information related to the type of frame, source and destination addresses, frame control, and sequence control. IEEE 802.11 standard defines three major frame types: (1) management frames which do not carry service data units, (2) control frames to assist delivery of data frames, and (3) some data frames with service data units, some without service data units, and a null frame to inform the access point of client's power save status.

IEEE 802.11 physical layer is divided into two sublayers: physical layer convergence protocol (PLCP) sublayer and physical medium dependent (PMD) sublayer (see Fig. 8.6). The PLCP sublayer receives a frame for transmission from the MAC sublayer and creates the PLCP protocol data unit (PPDU). The PMD sublayer then modulates and transmits the data as bits. The MAC protocol data unit that is delivered to the physical layer is referred to as the PLCP service data unit (PSDU). As part of the processing, the PLCP sublayer adds a preamble and header to the PSDU. When the PLCP layer receives the PSDU from the MAC layer, the appropriate PLCP preamble and header are added to the PSDU to create the PPDU. When transmitting data, the transmitting station provides the receiving station special synchronization sequences at the beginning of each transmission.

The access point periodically broadcasts a special signal called beacon (once every 102.4 ms). When the Wi-Fi communication module is turned on, the device first detects and decodes the beacon signal and establishes physical synchronization with the sender. After establishing synchronization, the access point and the device initiate the authentication procedure followed by the association procedure. There are two types of scanning: passive and active scanning. As shown Fig. 8.8, during passive scanning, the device scans and detects the beacon signal from the access point and establishes synchronization based on the beacon signal. In the active scan mode, the device broadcasts a probe request to all access points or a specific one. If there is any access point that detects the probe request, it sends a probe response to the device.

Once the client and the access point go through authentication and association procedure, the client can send or receive data. Unlike cellular standards, IEEE 802.11 does not support dedicated control/traffic channels and it does not have the MAC scheduling functionality in previous generations of Wi-Fi. However, IEEE 802.11ax adds an OFDMA scheduling capability and more granular resource allocation scheme. The stations are allowed to transmit at any time as long as the medium is not occupied by transmissions from other stations. To determine whether the medium is free and to overcome the hidden-node problem, the station transmits a short request to send (RTS) frame containing source address, destination address, and the duration of upcoming data transmission. Other stations located around the transmitting station may receive the RTS burst and check if the RTS is meant for them. If the RTS is meant for a station and the medium is free, the receiving device would transmit

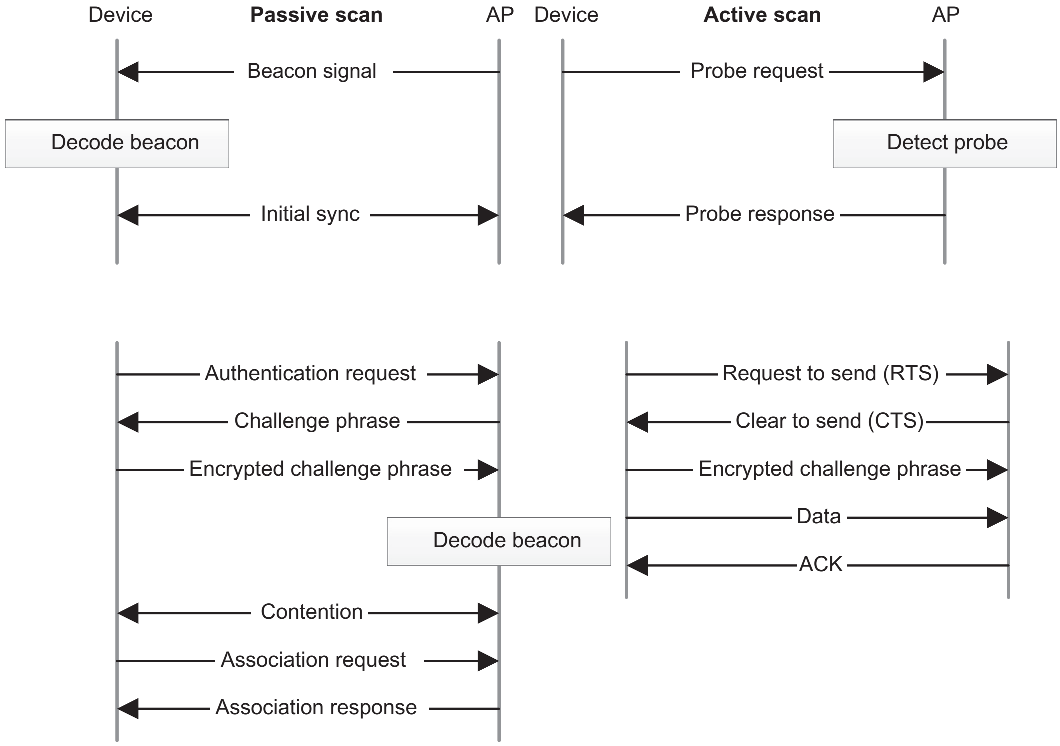

Figure 8.8
Scanning and association procedures [30].

a CTS frame containing the duration of the transaction. At this time, other devices in the vicinity of the communicating stations know that the medium will be occupied for certain time duration and set their NAV counters, which is a MAC-level contention control timer accordingly so that it would not try sensing the medium and transmitting during that period (see Fig. 8.9).

When a packet arrives at the MAC layer from higher layers, a sequence number is assigned to it, and if the packet length is larger than a single MAC frame, it is segmented into multiple fragments. In this case, a fragment number is assigned to each segment. When a packet is segmented into multiple MAC frames, those fragmented frames are assigned the same sequence number and different values for the fragment number. IEEE 802.11 can transmit a maximum of 2304 bytes of higher layer data.

8.1.4 LTE and NR Solutions for Operation in Unlicensed Spectrum

The traditional methods of interworking between cellular networks and Wi-Fi have proved to be cumbersome, with practical limitations in handling the mobility of the IP flows

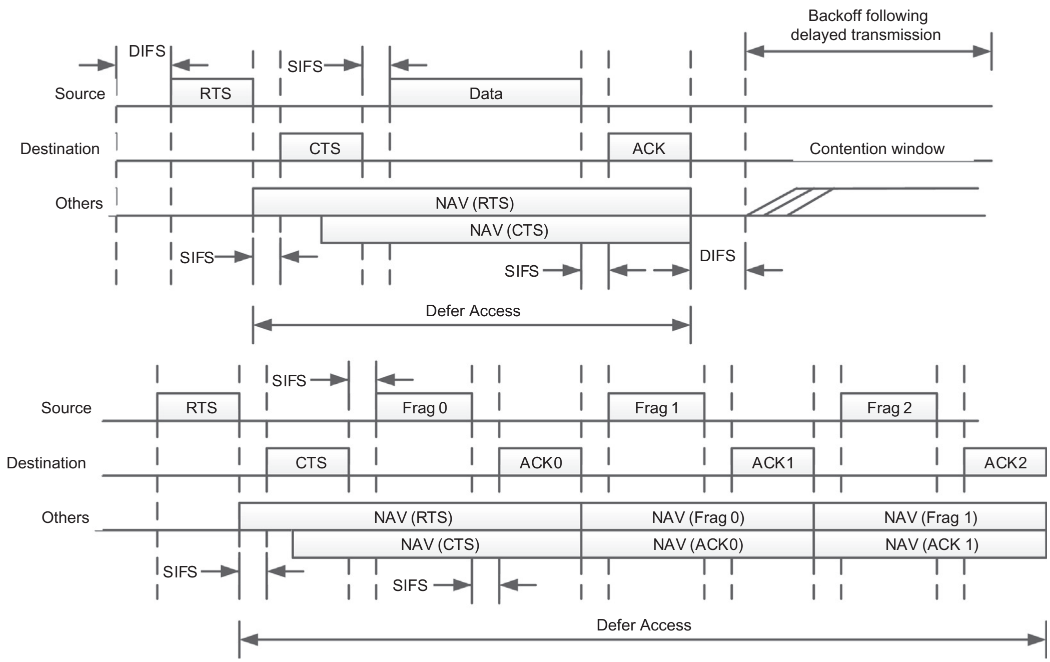

Figure 8.9
Medium access and contention control in IEEE 802.11 [30].

between cellular and Wi-Fi networks. All these schemes have suffered from complexity to define which Wi-Fi networks can be selected for traffic offload, and in which condition a Wi-Fi network should be selected so that it provides the best performance. For these needs, 3GPP has specified access network discovery and selection function (ANDSF), where an ANDSF server in the operator network controls the connection manager at the device. The ANDSF may have location-dependent network selection policies, defining how and in which priority order to select Wi-Fi networks. It is noted that the UE local operating environment and user preferences are important. The ANDSF has recently included comparative signal and load thresholds to instruct the UE when it should use the cellular base station and when to use the selected Wi-Fi access points for any given flow. Due to the lack of commercial interest in ANDSF, 3GPP has decided to integrate Wi-Fi into cellular networks by RAN-level features, which can provide scalability as a Wi-Fi access node acts in a similar manner as an eNB does, rather in the packet data network. A Wi-Fi access point may be integrated into an eNB. This type of interworking enables timely accounting of radio aspects in the offloading decisions and transparent integration of the Wi-Fi access with a single node connection to the cellular core network (in this case, the eNB), which not only reduces control signaling but simplifies network management operations. In this section, we focus on 3GPP RAN-level features, for example, LTE-Wi-Fi aggregation (LWA) and LTE-Wi-Fi radio-level integration with IP security tunnel (LWIP) introduced by 3GPP in Rel-13 and extended in Rel-14 [16,22]. In both features, the aggregated LTE link (licensed

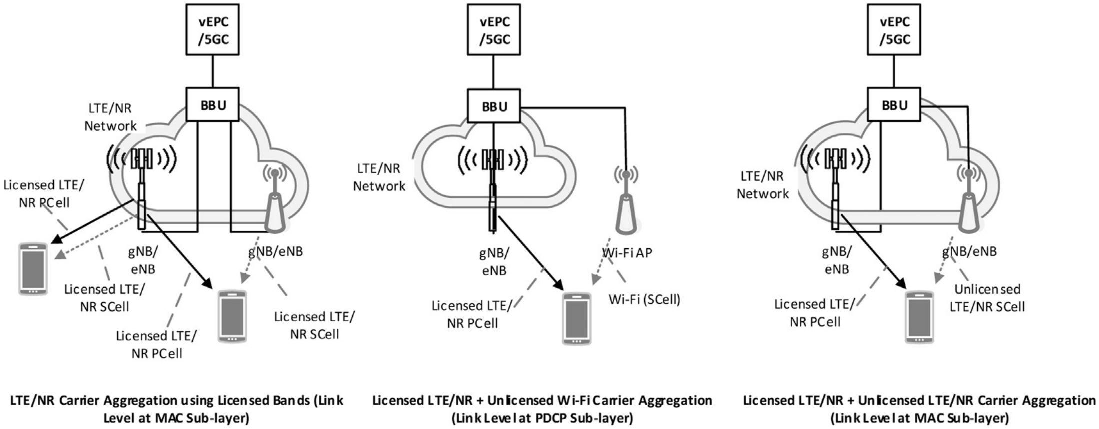

Figure 8.10
Comparison of various solutions for cellular operation in unlicensed spectrum [18].

operation) provides robust mobility and coverage, whereas the aggregated Wi-Fi link (unlicensed operation) allows routing of high data rate traffic, providing higher user throughput and more efficient use of both types of radio access. Despite their commonalities, LWA and LWIP have significant differences, mainly in the protocol layer at which the aggregation occurs and in the adopted user-plane security mechanisms. Fig. 8.10 summarizes various unlicensed access mechanisms that have been studied in 3GPP. In the following sections, we discuss in more details various schemes that have been used to enable LTE and NR access and operation in unlicensed spectrum.

8.1.4.1 License-Assisted Access

Licensed assisted access was introduced in LTE Rel-13. It uses carrier aggregation in the downlink to combine an LTE carrier in the unlicensed spectrum with LTE carrier(s) in the licensed spectrum (see Fig. 8.12). This aggregation of spectrum provides higher data rates, improved indoor connectivity, and network capacity. This is done by maintaining a persistent anchor in the licensed spectrum that carries the control and signaling information and combining it with one or more carriers from the unlicensed spectrum. The LAA has been designed as a single global solution that can adapt to unique regional regulatory requirements while coexisting with Wi-Fi and other unlicensed-band radios. For regulatory compliance and coexistence with other devices operating in the unlicensed band, devices supporting LAA must utilize LBT, which is mandated in Europe and Japan. The LBT used in LAA is similar to the method used by Wi-Fi nodes. A new frame structure (type 3) was defined exclusively for LAA cells, supporting discontinuous time-limited transmissions to ensure that the LTE access nodes do not dominate the channel. It also enables the use of incomplete subframes below 1 ms for more flexible adaptation to transmission opportunities after a successful LBT. The enhanced LAA (eLAA) in Rel-14 extended the downlink-only LAA to the uplink. For LAA operation in some geographical regions (e.g., Japan),

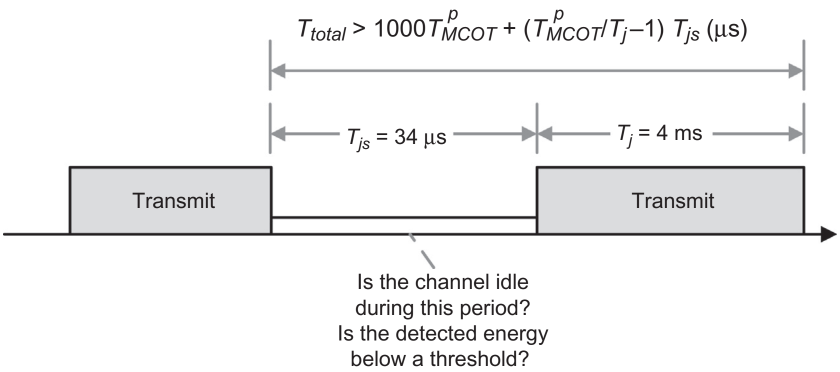

Figure 8.11
Discontinuous transmission in LAA [22].

discontinuous transmission is part of the specification. An eNB can transmit again on the LAA SCell for a maximum duration of $T_j = 4$ ms immediately after sensing the channel to be idle for a sensing interval of $T_{js} = 34\ \mu s$ as shown in Fig. 8.11.

The Rel-13 LAA functionality relies on LBT, frame structure type 3 along with discontinuous transmission with limited use of channel, use of incomplete subframes, downlink only, no PBCH (PBCH is not transmitted within frame structure type 3), use of Band 46 (5.150−5.925 GHz), and discovery reference signals (DRS) to enable radio resource management. In discontinuous transmission, the first subframe in a burst can last 1 ms (starts at symbol 0) or 0.5 ms (starts at symbol 7), which is signaled to the UE via RRC message *subframeStartPosition* in the dedicated physical configuration. The last subframe in a burst can last 1 ms or the duration of a special subframe with normal cyclic prefix (3, 6, 9, 10, 11, 12) OFDM symbols, which is signaled to the UE via DCI format 1C scrambled with CC-RNTI [8].

In LAA, the configured set of serving cells for a UE always include at least one SCell operating in the unlicensed spectrum. The LAA SCells act as regular SCells where the eNB and the UE use LBT before performing transmission in the SCell. The combined time of transmissions by an eNB may not exceed 50 ms in any contiguous 1 second period on an LAA SCell. The LBT type (i.e., type 1 or type 2 uplink channel access) which the UE applies is signaled via uplink grant for physical uplink shared channel (PUSCH) transmission on LAA SCells. For type 1 uplink channel access on autonomous uplink (AUL)[7], the eNB signals the *channel access priority class* for each logical channel and the UE must select the lowest *channel access priority class* of the logical channel(s) with MAC SDU multiplexed into the MAC PDU. The MAC control elements, except padding buffer status report (BSR), use the highest *channel access priority class*. For type 2 uplink channel access on AUL, the UE

[7] In autonomous uplink, uplink transmissions are allowed without requiring a prior scheduling request or an explicit scheduling grant from the eNB.

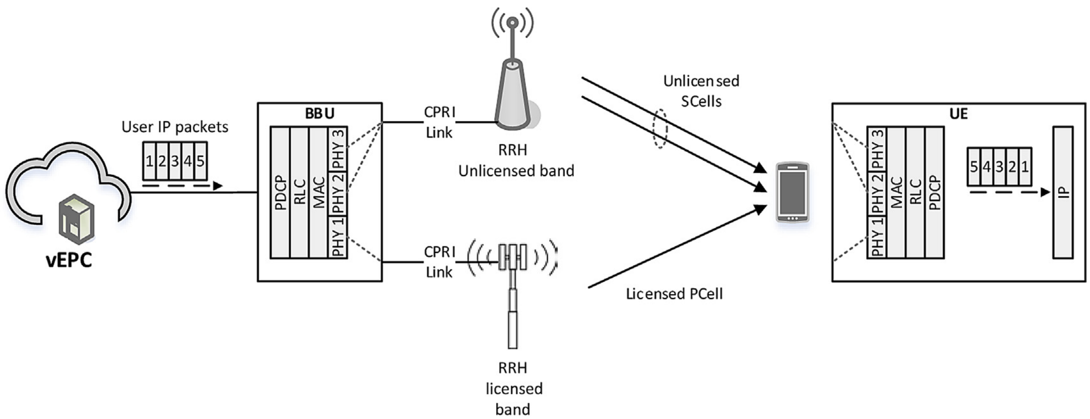

Figure 8.12
Illustration of LAA operation concept [18].

may select logical channels corresponding to any *channel access priority class* for uplink transmission in the subframes signaled by eNB in common downlink control signaling. For uplink LAA operation, the eNB does not schedule the UE more than the minimum number of subframes necessary to transmit the traffic corresponding to the selected *channel access priority class* or lower than the following: (1) The *channel access priority class* signaled in uplink grant based on the latest buffer status report and received uplink traffic from the UE if type 1 uplink channel access procedure is signaled to the UE. (2) The *channel access priority class* used by the eNB based on the downlink traffic, the latest BSR and received uplink traffic from the UE, if type 2 uplink channel access procedure is signaled to the UE [5].

Four *channel access priority classes* are defined as shown in Table 8.3, which can be used when performing uplink and downlink transmissions on unlicensed carriers. In LTE-based LAA, each *channel access priority class*, used by user traffic, is associated with the standardized LTE QoS class identifiers (QCIs); i.e., channel access priorities 1,2,3,4 are associated with QCI values (1,3,5,65,66,69,70),(2,7),(4,6,8,9),(-), respectively [5]. A non-standardized QCI (operator defined QCI) should use a suitable *channel access priority class* associated with the standardized QCIs, which best matches the traffic class. If a downlink transmission on physical downlink shared channel (PDSCH) is intended for which channel access has been obtained using *channel access priority class* $p \in \{1, 2, 3, 4\}$, the LTE system must ensure that the transmission duration does not exceed the minimum duration needed to transmit all available buffered traffic; and further the transmission duration does not exceed the maximum channel occupancy time (MCOT)[8] as defined in Table 8.3 for each *channel*

[8] Maximum MCOT is the maximum continuous transmission time after channel sensing, while Wi-Fi may transmit for much shorter time duration. The maximum continuous transmission time in license-assisted access is limited to 8 or 10 ms regardless of frame size and data rate.

Table 8.3: Channel access priority classes in the downlink/uplink [3,4].

Link Direction	*Channel Access Priority Class p*	m_p	min(CW_p)	max(CW_p)	T^p_{MCOT} (ms)	Allowed CW_p Sizes
Downlink	1	1	3	7	2	{3,7}
	2	1	7	15	3	{7,15}
	3	3	15	63	8 or 10	{15,31,63}
	4	7	15	1023	8 or 10	{15,31,63,127,255,511,1023}
Uplink	1	2	3	7	2	{3,7}
	2	2	7	15	4	{7,15}
	3	3	15	1023	6 or 10	{15,31,63,127,255,511,1023}
	4	7	15	1023	6 or 10	{15,31,63,127,255,511,1023}

access priority class. The downlink burst in the above refers to the continuous transmission by LTE after a successful LBT. For uplink PUSCH transmission, there is no additional restriction on the UE regarding the type of traffic that can be carried in the scheduled subframes [10].

LTE Rel-15 further enhanced the uplink transmission in an LAA SCell in the unlicensed spectrum by specifying support for multiple uplink starting and ending point in a subframe, and support for AUL transmission, including channel access mechanisms, core and RF requirements for base stations and UEs, and RRM requirements. The key functionalities introduced in LTE Rel-15 include additional starting and ending points for PUSCH transmissions on an LAA SCell (starting PUSCH transmission at the slot boundary; ending PUSCH transmission after the third symbol or at the slot boundary; and UE-based selection of the starting point for PUSCH transmission at the subframe or slot boundary depending on successful channel access); AUL access where a UE can be RRC-configured with a set of subframes and HARQ processes that it may use for autonomous PUSCH transmissions [8,11]. The AUL operation is activated and released with DCI format 0A (transmission mode [TM1]) or DCI format 4A (TM2). The UE skips an AUL allocation if there is no data in the uplink buffers. The PRB allocation and MCS as well as DMRS cyclic shift and orthogonal cover code are indicated to the UE via AUL activation DCI. The UE informs the eNB along with each AUL transmission of the selected HARQ-process ID, new data indicator, redundancy version, UE ID, PUSCH starting and ending points, as well as whether the UE-acquired channel occupancy time can be shared with the eNB. The eNB may provide the UE with HARQ feedback for AUL-enabled HARQ processes, transmit power command, and transmit PMI [5,6].

LTE Rel-13 introduced UE RSSI measurements with configurable measurement granularity and time instances of the reports which can be used for the assessment of hidden nodes by an eNB which is located near specific UEs. For example, if UE measurement shows a high RSSI value when the serving cell is inactive due to LBT, it can imply the presence of hidden nodes and can be considered for channel (re)selection. The DFS is a regulatory requirement for certain frequency bands in some regions, for example, to detect interference from radar systems and to avoid cochannel operation with these systems by selecting a different carrier on a relatively slow time scale. The corresponding time scales for DFS are in the order of seconds and can, therefore, be at an even slower time scale than carrier selection. This functionality is an implementation issue and does not impact the specifications. As we mentioned earlier, LBT procedure is defined as an algorithm by which a UE performs one or more CCAs prior to transmitting on the channel. It is the LAA equivalent of the DCF and EDCA MAC protocols in Wi-Fi (see Fig. 8.13).

3GPP has specified four categories of LBT as follows:

- Cat-1: no LBT
- Cat-2: LBT without random backoff
- Cat-3: LBT with random backoff and fixed CW
- Cat-4: LBT with random backoff and variable CW

A simple approach to ensure coexistence with Wi-Fi is to make the LAA LBT procedure for both data and discovery reference signal[9] as similar as possible to IEEE 802.11 DCF and EDCA protocols. This was the underlying design principle in Rel-13 LAA LBT mechanism for detecting the presence of Wi-Fi which can be summarized as follows:

- An LAA-enabled node must sense the carrier to be idle for a random number of 9 μs CCA slots prior to data transmission.
- If the energy in a CCA slot is sensed to be above an energy detection (ED) threshold, then the process is suspended and the counter is stopped. The backoff process is resumed and the counter is decremented once the carrier has been idle for the duration of the deferred period. The energy detection threshold is both channel type and output power related, that is, -72 dBm for 23 dBm PUSCH and -62 dBm for DRS. An important component of LBT design is the choice of ED threshold, which determines the level of sensitivity to declare the existence of ongoing transmissions. 3GPP has studied mechanisms to adapt the ED threshold. An eNB accessing a carrier on which LAA SCell(s) transmission(s) are performed, sets the ED threshold $ED_{threshold}$ to less than or equal to the maximum ED threshold $\max(ED_{threshold}) = \min(T_{\max} + 10\,\text{dB}, \eta_r)$, if the absence of any other technology sharing the carrier can be guaranteed on a long-term

[9] A downlink transmission by the eNB may include a discovery signal and without physical downlink shared channel on a carrier on which license-assisted access SCell(s) transmission(s) are performed, immediately after sensing the idle channel for a sensing interval $T_{drs} = 25\ \mu s$ and if the duration of the transmission is less than 1 ms. The parameter T_{drs} consists of a duration $T_f = 16\ \mu s$ immediately followed by one slot duration $T_{slot} = 9\ \mu s$ and T_f includes an idle slot duration T_{slot} at start of T_f. The channel is considered idle for T_{drs}, if it is sensed to be idle during the slot durations of T_{drs}.

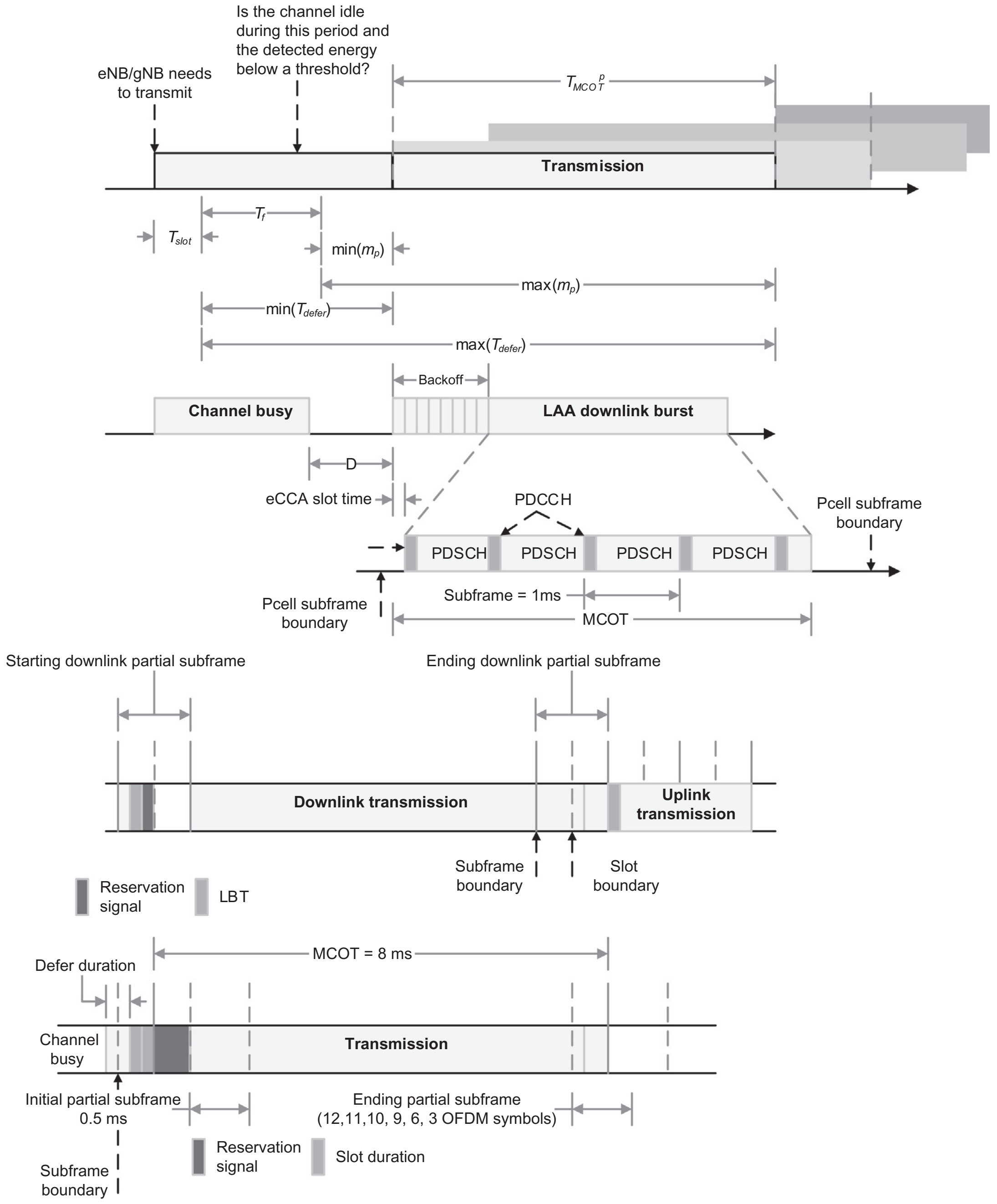

Figure 8.13
Frame structure type 3 and LBT mechanism in LAA [22].

basis, where η_r is maximum ED threshold defined by regulatory requirements in dBm when such requirements are defined; otherwise [4]:

$$ED_{threshold} = \max\left\{\begin{array}{l} -72 + 10\log_{10}(BW\ \mathrm{MHz}/20\ \mathrm{MHz})\ \ \mathrm{dBm}, \\ \min\left\{\begin{array}{l} T_{\max}, \\ T_{\max} - T_A + \left(P_H + 10\log_{10}(BW\ \mathrm{MHz}/20\mathrm{MHz}) - P_{TX}\right) \end{array}\right\} \end{array}\right\}$$

where P_H is a reference power equal to 23 dBm, $T_A = 10$ dB for transmission(s) including PDSCH or $T_A = 5$ dB for transmissions including discovery reference signal transmission(s) and excluding PDSCH, P_{TX} is the configured maximum transmit power for the carrier in dBm, and it is given by $T_{\max} = -75\ \mathrm{dBm/MHz} + 10\log_{10}(BW)$, where BW is the channel bandwidth in MHz. In a nutshell, the energy detection threshold can be increased if the bandwidth increases and/or the transmit power decreases. The detected energy level needs to be below this threshold for a certain period of time with a slot duration $T_{slot} = 9\ \mu s$ and defer time $T_{defer} = T_f + m_p$, where $T_f = 16(\mu s)m_p$ is based on the *channel access priority class* and is, therefore, traffic-type dependent and has a duration of at least one slot. The defer time is required to specifically protect Wi-Fi ACK/NACK transmission between the access points and the clients. As a result, the channel needs to be idle for an initial CCA period of 34 μs and a maximum wait time of 88 μs before an LAA-capable eNB can start its transmission. If the channel is sensed to be clear, the transmitter can only transmit for a limited amount of time defined as the maximum channel occupancy time T^p_{MCOT}. If the channel is sensed to be occupied during that time or after a successful transmission, the enhanced CCA period is started by generating a random number that is within the contention window. Because there are different traffic types (VoIP, video, background traffic, etc.), different *channel priority access classes* have been defined with different CW sizes and T^p_{MCOT} (see Table 8.3).

- If the most recent downlink transmission burst showed 80% or more decoding errors, as reported via HARQ feedback (NACKs) from UEs, then the CW is doubled for the next LBT (see Fig. 8.14).
- Once downlink transmission is complete, a new random backoff is chosen and used with the next transmission.
- A single, short CCA period of 25 μs can be used to transmit control information without accompanying data such as DRS. This is aligned with the CCA duration used for Wi-Fi beacon frames.
- Rel-13 LTE defined an LAA equivalent to the four Wi-Fi priority classes in the form of four sets of minimum and maximum CW sizes, maximum channel occupancy times, and deferred period CCA slots.

An LAA/Wi-Fi coexistence study suggests that the coexistence performance is more sensitive to factors that affect the channel occupancy (e.g., control signals) rather than to the

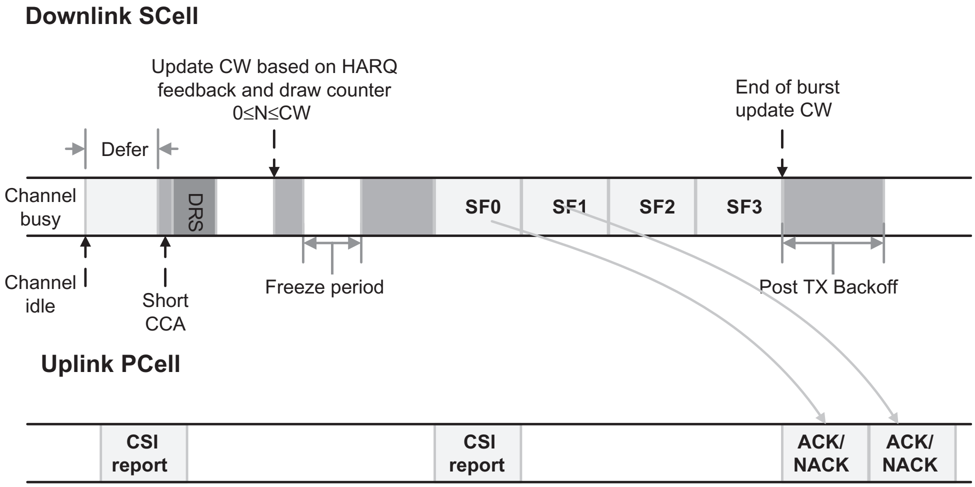

Figure 8.14
An example of LAA downlink transmission with LBT CW updates based on HARQ ACK/NACK feedback. The UE provides HARQ feedback and CSI reports on the licensed carrier [17,23].

choice of parameters in the LBT CCA and backoff algorithms. Consequently, the coexistence is highly affected by the behavior of the upper-layer protocols; bursty traffic pattern; HARQ-based CW slot update; and either CTS-to-self or support for lower Wi-Fi energy detection thresholds, which seems to be a fundamental feature to be supported by LAA to allow coexistence with Wi-Fi and protect the LAA performance in the presence of hidden nodes [12].

To minimize interference to Wi-Fi transmissions, an LTE system can mute its operation in almost blank subframes (ABS). These subframes are called almost blank because LTE can still transmit some broadcast signals, control signals, and synchronization signals over these subframes. However, these signals only use a small fraction of system resources in the time/frequency domain and reduced power. Therefore, cochannel interference is much less during the ABS transmission periods.

The LTE-based LAA defines methods for UEs in the LAA SCell coverage to provide radio resource management measurements and reporting. The Rel-12 discovery reference signals, originally designed for small cells, are being used with certain modifications in LTE-based LAA SCells. As shown in Fig. 8.15, the LTE-based LAA DRS can be transmitted within a periodically occurring time window called the DRS measurement timing configuration occasion that has a duration of 6 ms and a configurable period of 40, 80, or 160 ms. The radio frame and subframe in which DRS can be transmitted depends on the RRC parameters (*dmtcOffset, dmtcPeriodicity*) that are signaled to the UE. The LTE-based LAA DRS can be transmitted following a single idle observation interval of at least 25 μs. To compensate for

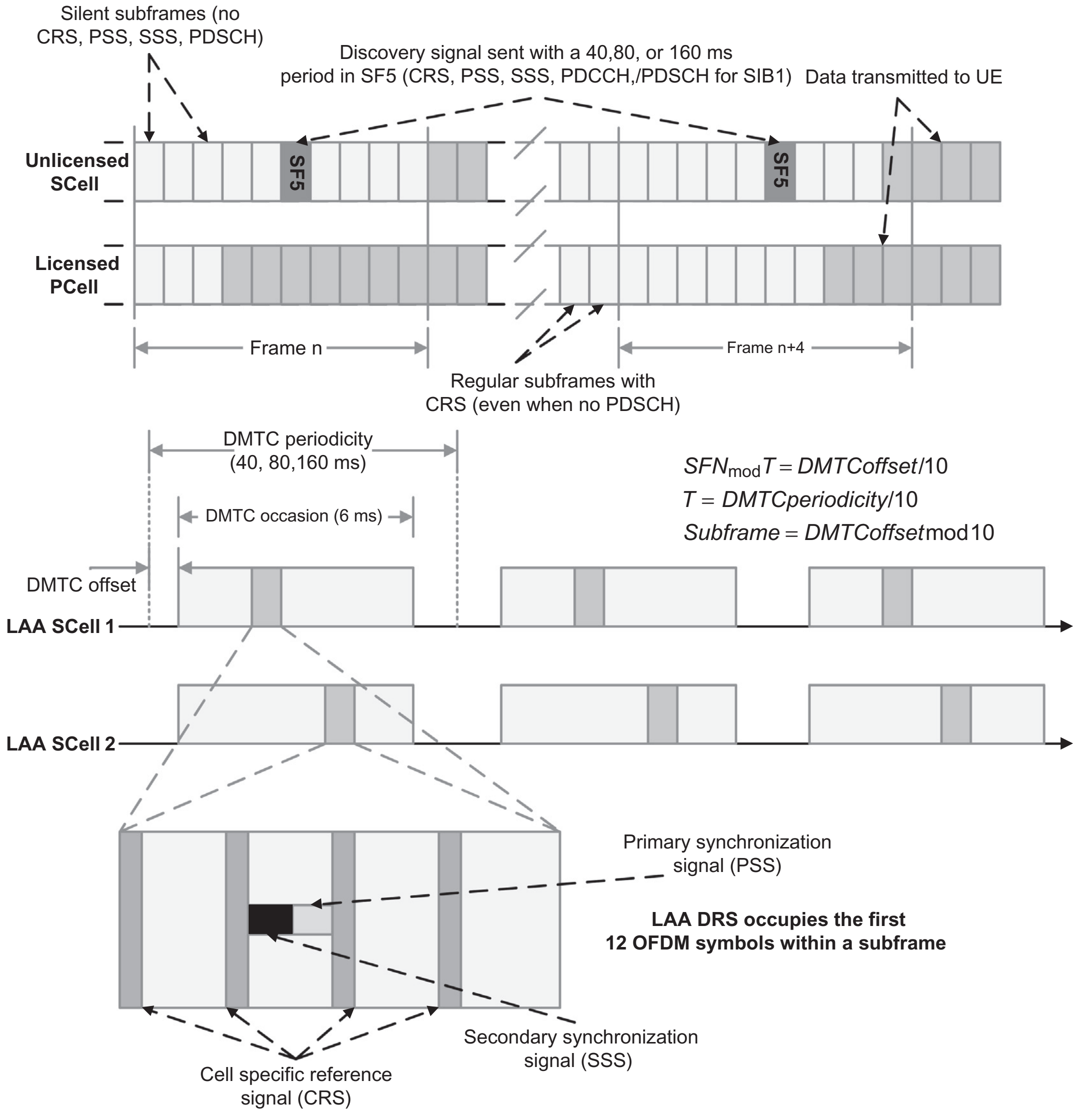

Figure 8.15
Structure and timing of discovery signals in LAA SCell [14,20].

potential DRS transmission blocking due to LBT and increase the probability of successful of DRS transmission, the network can attempt DRS transmission in any subframe within the DMTC occasion [26].

LAA operation on multiple unlicensed carriers is a key requirement for maximizing throughput. IEEE 802.11ac/ax supports transmission bandwidths of up to 160 MHz, which would span eight contiguous 20 MHz unlicensed channels in the 5 GHz band. The LAA multi-carrier transmission on multiple unlicensed SCells adheres to the principle of fair channel utilization while identifying improved transmission opportunities across available spectrum. Rel-13 LAA supports two methods for identifying and utilizing secondary channels: (1) prior to transmission, a single random backoff is completed on any carrier along with CCA on other channels; (2) multiple SCells must individually perform random backoff before transmitting simultaneously. The single and multi-carrier LBT schemes are illustrated and compared in Fig. 8.16 for a scenario in which three LAA SCells are assigned a common random backoff counter. The performance of multi-carrier LBT over 80 MHz has been evaluated and shown in Fig. 8.17. The overall system performance in terms of mean user throughput as a function of served traffic per access point per operator show that, from the coexistence point of view and the impact on the non-replaced Wi-Fi network, both classes of multi-channel LAA LBT schemes are viable and can increase the performance of a multi-carrier Wi-Fi network compared to the case when it is coexisting with another Wi-Fi network [17,23].

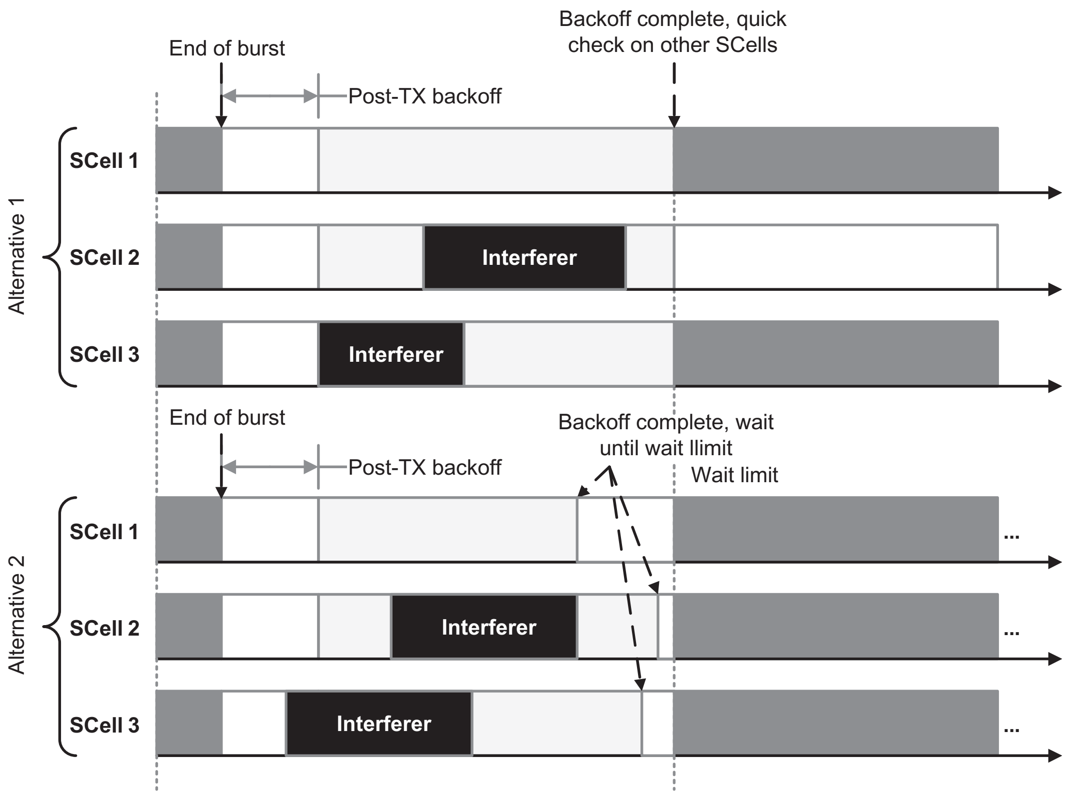

Figure 8.16
Comparison of LAA multi-carrier LBT access schemes with single and multiple random backoff channels [17,23,31,32].

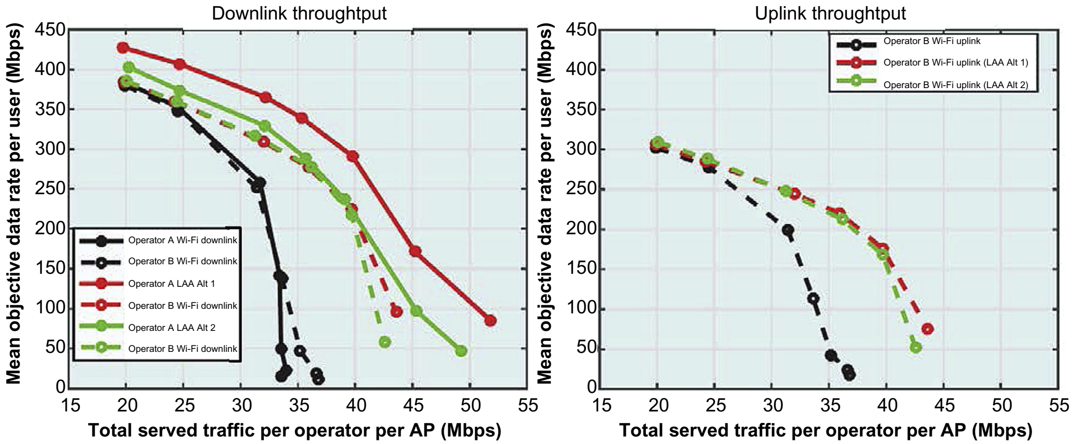

Figure 8.17
Mean user throughput versus served traffic per access point per operator for the indoor multi-carrier deployment scenario with FTP traffic using up to 80 MHz transmission bandwidth [17,23].

As mentioned earlier, LBT is a mechanism used by devices operating in the unlicensed bands to determine the presence of other signals in the channel prior to transmission and to avoid collisions with other transmissions. This protocol allows several users and different technologies to use the same channel without pre-coordination. In LAA, the LBT procedure is initialized when the SCell has data to transmit. Prior to that, the cell is completely turned off to all transmissions, including cell reference signals. Then, the LAA cell will initiate a CCA to determine if the channel is idle. If there are no signals detected in the channel, then the transmission can proceed. This procedure is illustrated in Fig. 8.18. If the channel is not idle, the device performs a slotted random backoff procedure, in which a random number of slots are withdrawn from the contention window. The contention window is increased exponentially with the occurrence of collisions and is reset to the minimum value once the transmission succeeds. Given the random nature of the backoff procedure, different devices will have different backoff intervals, improving channel adaptation [14,20].

8.1.4.2 LTE-Wi-Fi Aggregation

An alternative approach to deploying LTE in the unlicensed spectrum, which was more acceptable to the Wi-Fi industry, was through the aggregation of LTE and Wi-Fi carriers. This solution was meant to enhance LTE performance by partly offloading traffic to an available Wi-Fi link. In this scheme, an LTE payload is split at the PDCP level and some traffic is tunneled over the Wi-Fi link while the remaining traffic is sent over the native LTE connection. The LWA approach uses Wi-Fi access points to augment LTE RAN by encapsulating LTE data in IEEE 802.11 MAC frames, such that it appears as a Wi-Fi frame

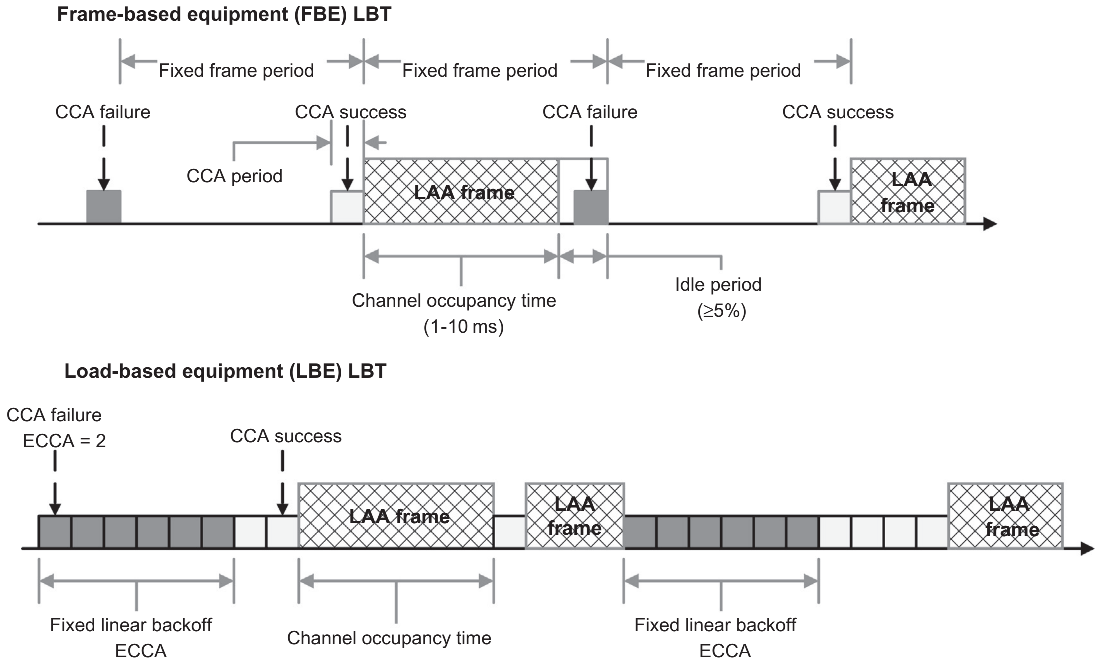

Figure 8.18
Illustration of channel sensing before transmission until the channel is unoccupied [14,20].

to another network. This method would allow both technologies to operate in their respective spectrum, that is, Wi-Fi operating in the unlicensed band and LTE continues to operate in a licensed band, while there are no changes in their respective access mechanisms. This is the significant difference compared to LTE-unlicensed and LAA schemes. In the case of LWA solution, the aggregation takes place at the radio link level. The Wi-Fi access points can use the LTE core network functions (e.g., authentication, security, etc.). It will be discussed in Section 8.2 that the LWA architecture consists of LWA eNB, LWA-aware Wi-Fi access points, and LWA UEs. The LWA eNB and Wi-Fi AP can be co-located or non-co-located. If non-co-located, data is delivered through IP tunnel between two systems. The LWA eNB performs scheduling of PDCP packets and transmits some of the IP packets over the LTE air-interface and others over the Wi-Fi after encapsulating them in Wi-Fi MAC frames. All packets, received over either LTE or Wi-Fi, are then aggregated at the PDCP sublayer of the LWA UE. The Wi-Fi APs are connected to LWA eNBs and report information on channel conditions to the LWA eNB. The LWA eNB then determines whether to use the Wi-Fi link or not. The LWA eNB can improve LTE performance by managing radio resources in real-time according to the RF and load conditions of both LTE and Wi-Fi. A Wi-Fi AP can work as a native Wi-Fi AP while not serving the LWA purpose. This

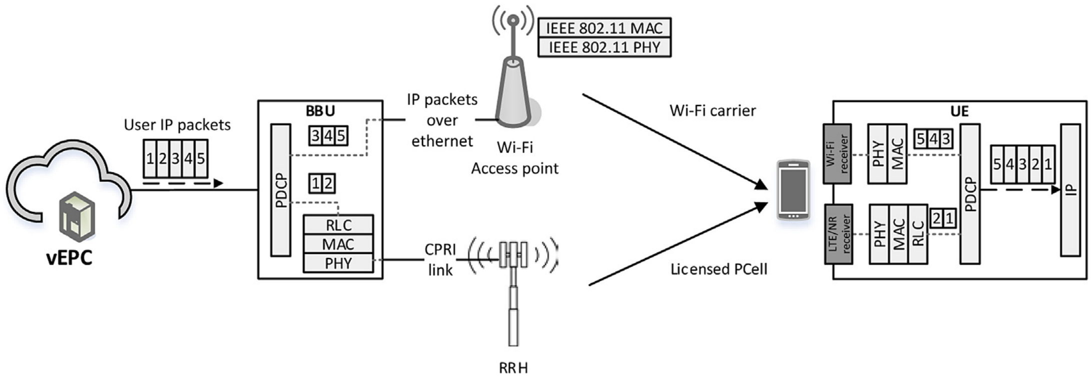

Figure 8.19
Illustration of LWA principle of operation [18].

eliminates potential coexistence issues in the unlicensed bands. However, as LTE data must be split at eNB and then aggregated at UE, the involved nodes such as eNB, Wi-Fi AP, and UE must be LWA-enabled. The LWA architecture, protocol, and operations will have to be defined as well. Fig. 8.19 shows the high-level architecture and operation of LWA scheme [18].

8.1.4.3 LTE Unlicensed and MulteFire

In 2014, a group of companies formed the LTE-U Forum to develop technical specifications based on LTE Rel-12 in the 5 GHz band. LTE-U Forum initially focused on non-LBT markets without modifying the LTE physical layer and MAC functionalities. The deployment scenarios included supplemental LTE downlink operating in an unlicensed spectrum comprising multiple contiguous 20 MHz bands. The LTE network with an uplink and downlink anchored on the licensed spectrum (up to 20 MHz) for delivering essential control signaling and synchronization related to radio resource management and connection/mobility provides reliability, mobility, and coverage, whereas the unlicensed spectrum was exclusively used for increasing the downlink data rates.

LTE-U was designed to comply with the US regulations and targets other regions of the world with no LBT requirements. However, it does not necessarily meet the needs of other regions which do require LBT feature such as Europe and Japan. While LTE-U and LAA are both LTE-based solutions for operation in the unlicensed band, they differ in the way they meet the regulatory requirements. LTE-U is well suited for regions that do not require LBT and address coexistence issues with Wi-Fi using an algorithm called carrier sensing adaptive transmission (CSAT) in the LTE-U eNB, which is based on the use of duty cycle that adapts the duration of the ON period by sensing the average power in the channel as shown in Fig. 8.20. LTE-U also limits the duration of the ON period to 20 ms so that low

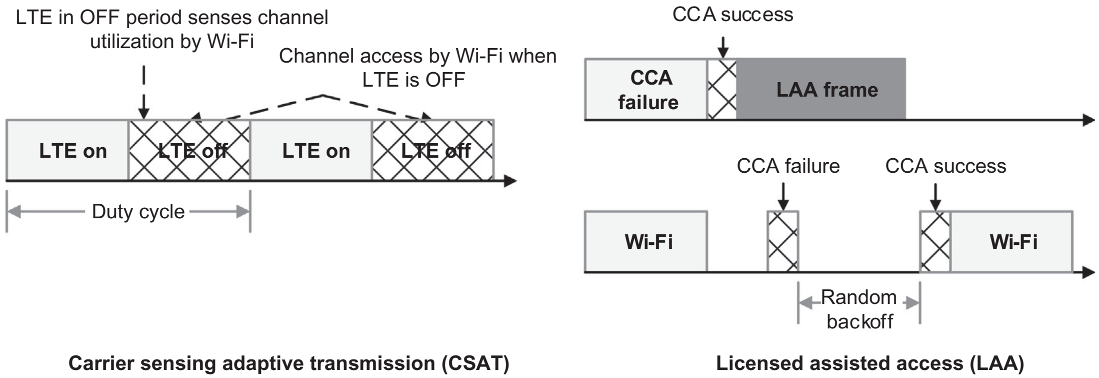

Figure 8.20
Comparison of CSAT and LBT mechanisms [17,23].

latency applications can coexist. On the other hand, LAA is a global solution and includes support for LBT and a more flexible frame structure to better adapt to channel availability. LAA is generally preferred by operators as it is the only method that provides full cellular capabilities, whereas LWA or LWIP are less frequently used because they require either a Wi-Fi network or partnership with a Wi-Fi operator.

In an ultra-dense deployment of Wi-Fi and LTE-U small cells, there is a possibility that no clean channel can be found. In such cases, LTE-U can share the channel with the neighboring Wi-Fi or another LTE-U system by using the CSAT algorithm. Typical cochannel coexistence techniques in unlicensed bands such as LBT and CSMA, used by Wi-Fi systems, are based on the contention-based access. In these techniques, transmitters are expected to sense the medium to ensure that there is no activity prior to transmission. The goal of these algorithms is to provide coexistence across different technologies in a time-division multiplexing (TDM) manner. LTE-U in unlicensed spectrum uses CSAT scheme that relies on the same concept of TDM coexistence and medium sensing. In CSAT, the small cell senses the medium for longer (than LBT and CSMA) duration (up to 200 ms), and according to the observed medium activities, the algorithm proportionally switches off LTE transmission. In particular, CSAT defines a time cycle where the small cell transmits in a fraction of the cycle and remains off in the remaining duration. The duty cycle of transmission relative to OFF interval is determined by the sensed medium activity of other technologies. The CSAT is conceptually similar to CSMA except that it has longer latency, an impact that is mitigated by avoiding channels where Wi-Fi APs use for discovery signals and QoS-enforced traffic. The LTE-U, which is deployed on the SCell, is periodically activated and deactivated using LTE MAC control elements. The procedures and timeline are chosen to ensure compatibility with legacy LTE UE behavior. During the LTE-U OFF period, the channel is released to neighboring Wi-Fi APs, which can resume normal transmissions. The small cell will measure Wi-Fi medium utilization during the LTE-U OFF period and adaptively adjust

ON/OFF duty cycle. The adaptive cycle can effectively accommodate the activation/de-activation procedures while controlling the data transmission delay. Because the anchor carrier in license band is always available, the supplemental downlink carrier in the unlicensed band can be used opportunistically. When the downlink traffic of the small cell exceeds a certain threshold and there are active users within the unlicensed band coverage area, the supplementary downlink (SDL) carrier can be turned on for offloading the traffic. When the traffic load can be managed by the primary carrier or there is no user within the unlicensed band coverage area, the SDL carrier is turned off. Opportunistic SDL mitigates the interference from LTE continuous cell-specific reference signal transmission in an unlicensed channel.

MulteFire was proposed by the MulteFire Alliance in late 2015 as a standalone version of LTE for small cells, which operates in the unlicensed spectrum and can provide service to users with or without a universal subscriber identity module card (i.e., an operator subscription). It combines the advantages of LTE technology and the simplicity of Wi-Fi deployments and can be deployed either by traditional mobile operators or neutral hosts. It specifies two different architectures: (1) a PLMN access mode, which allows mobile network operators to extend their coverage into the unlicensed band, especially in the case where a licensed spectrum is not available at certain locations; and (2) a neutral host network access mode, which is similar to Wi-Fi, a self-contained network deployment that provides access to the Internet. Because of the nature of transmission in the unlicensed band and the need to adhere to the LBT requirements, MulteFire has introduced some modifications to the radio interface of LTE [16].

8.1.4.4 NR-Unlicensed

The NR-U study item in Rel-16 is identifying and evaluating solutions for the NR when operating in the unlicensed spectrum. 3GPP will further investigate the coexistence with NR-based systems in the licensed and unlicensed bands as well as with LTE-based LAA and other incumbent RATs to ensure compliance with regulatory requirements. 3GPP Rel-15 NR introduced a flexible frame structure with various subcarrier spacing options and slot formats. It further introduced mini-slot configuration, whereby PDSCH resource allocation can start from almost any symbol in a slot. The NR-U is expected to support both baseline NR Type A (slot-based) and Type B (non-slot-based) resource allocation schemes. Even with restricted mini-slot length of 2, 4, and 7 symbols for downlink, the PDSCH transmission (without gap) can still start at almost any symbol position, if we allow multiple mini-slots to be allocated within a slot. In the uplink, however, the mini-slot length and starting symbol are not restricted, thus uplink transmission in NR-U (without gap) can start at any symbol position.

For sub-7 GHz unlicensed bands, 15 kHz SCS with normal cyclic prefix that was supported in LTE-based LAA and the same SCS must be supported in NR-U to achieve similar coverage when the component carrier bandwidth is 20 MHz. On the other hand, if a larger SCS is used, the OFDM symbol duration will be shorter, which increases the channel access opportunities, reduces latency, and enhances resource utilization. A larger SCS can facilitate single wideband-carrier operation. In carrier aggregation scenarios (similar to LTE-based LAA), the device performs LBT per component carrier and then transmits on any available component carrier. Operating a single carrier allows reducing the control overhead and avoiding the use of inter-carrier guard bands. For the same system bandwidth, a larger SCS requires a smaller FFT size, hence reducing the implementation complexity. The studies suggest that an NR system with SCS of 60 kHz operating as a wideband carrier obtains about 60% average downlink user throughput gain and 80% average uplink user throughput gain over LTE-based LAA system for the same system bandwidth [14,20]. The performance gain comes from the finer granularity of channel occupation in the time domain. In addition, the processing delay for the short symbol demodulation is reduced, so retransmission for short symbols in the same MCOT becomes possible and HARQ combining gain can be achieved with low latency. Furthermore, the overhead of guard band with 60 kHz SCS wideband carrier is also smaller than that of LTE-based LAA. However, in carrier aggregation scenarios, the performance gain of 60 kHz SCS relative to LTE-based LAA diminishes because of the spectrum efficiency loss from guard bands in 60 kHz SCS and 20 MHz bandwidth. The occupied channel bandwidth of an SS/PBCH block with subcarrier spacing 15 and 30 kHz is 3.6 and 7.2 MHz, respectively. An SS/PBCH block with subcarrier spacing 15 kHz in 5 GHz unlicensed band cannot meet the OCB requirements because system/nominal bandwidth in most cases would be greater than 5 MHz. The NR-U should support similar SCS in 6−7 GHz unlicensed bands. To support 60 kHz SCS for all NR-U signaling in operation below 6 GHz, some modifications in Rel-15 NR are required because NR does not support SS/PBCH block transmission using 60 kHz. In addition, the candidate SS/PBCH positions for a half frame are not defined for 60 kHz SCS. Note that the use of 60 kHz SCS for PRACH transmission in NR is also restricted to frequencies above 6 GHz. For outdoor deployments, even if the output power is limited, considerable delay spread can still be observed. For 60 kHz SCS with normal CP, the cyclic prefix is 1.17 μs corresponding to a range of 175.5 m, which is very typical in outdoor environments. The cyclic prefix of 60 kHz SCS with extended CP is 4.17 μs corresponding to a range of 625.5 m, which would be sufficient for most outdoor small cell deployments.

In NR, the SCS for each channel or signal is configured through the BWP information element (IE) configuration, and the subcarrier spacing in the BWP IE is used for all channels and reference signals unless explicitly configured. The reference SCS of the slot structure configuration is included in SIB1. Furthermore, the SCS for SIB1, Msg.2/Msg.4 for initial access, and broadcast SI-messages is included in the MIB. For NR-U, these SCS configuration schemes can be reused directly. In licensed bands, NR supports dynamic and semi-statically configured slot configuration. The semi-static DL/UL assignment is done via cell-specific and UE-specific RRC configuration. With the cell-specific configuration, the UE is

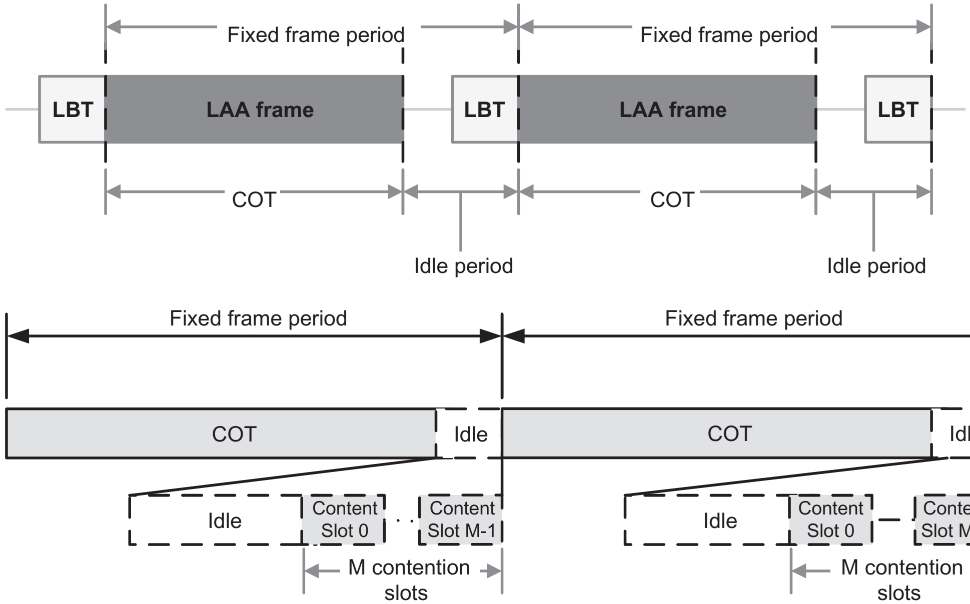

Figure 8.21
Illustration of timing relation for FBE [24,25].

allocated flexible resources that can be assigned to downlink or uplink using UE-specific configuration or dynamic signaling. The UE-specific RRC signaling or dynamic signaling includes per-slot-basis indication that can override the unknown allocation in the cell-specific configuration. Resources in the slot configuration that are without downlink/uplink indication are considered flexible resources.

Frame-based equipment (FBE)[10] is a channel access mechanism wherein the transmit/receive frame structure has a periodic timing with a periodicity known as the fixed frame period (FFP), which is between 1 and 10 ms. The transmitting device performs a single-shot LBT before starting transmission in a channel at the beginning of an FFP, and the channel occupancy time (COT) associated with a successful LBT (see the example shown in Fig. 8.21). In addition to the load-based equipment (LBE) operation mode, NR-U can also support the FBE operation mode for use cases in which other LBE-based networks (e.g., Wi-Fi, LTE-based LAA) are excluded such as in a factory or private NR-U network. In comparison to the LBE mode, the FBE operation mode can achieve higher spectrum utilization in such scenarios considering much simpler LBT process. The necessity of signaling to indicate FFP and channel occupancy time to the UE is being studied.

[10] FBE is a scheme where the transmit/receive frame structure is not directly demand-driven but has fixed timing as opposed to LBE where the transmit/receive frame structure is not fixed in time but demand-driven.

Dynamic and semi-statically configured downlink/uplink configuration can be used in NR-U. For example, some semi-static DL/UL assignments can be used to indicate downlink slots to the UE to receive the SS/PBCH blocks, and other slots can be assigned to the UE to transmit PRACH or granted uplink transmission. If gNB performs LBT successfully on the semi-statically configured downlink slot, it can dynamically override the flexible resource (s) through DCI format 2_0. Furthermore, the use of a flexible frame structure in NR-U can take advantage of MCOT. Multiple DL-to-UL switching points in the MCOT can be permitted to reduce the scheduling and feedback delay. However, more DL-to-UL switching points create more gaps to perform LBT upon each change of transmission direction which may result in resource wastage or channel loss during this time. Therefore, there is a tradeoff between fast switching and overhead for potential use cases. Because the MCOT duration is different for various channel access priorities and regional regulations, different maximum number of DL-to-UL switching points for each MCOT duration should be defined. In LTE-based LAA, the eNB can only start transmission at slot boundaries (symbol 0 or 7) with 15 kHz subcarrier spacing. The reservation signal is transmitted before the downlink transmission start position, that is, the slot boundary, to reserve the carrier and prevent other devices from occupying the frequency band, which is considered an overhead in LTE-based LAA system. Therefore, the overhead of reservation signal should be minimized. In NR-U, different slot types including slot and mini-slot (non-slot-based scheduling) can be utilized to minimize the reservation signal length. The gNB or UE should be able to send DL/UL transmissions as soon as possible whenever LBT/CCA procedure is completed, resulting in different slot duration. As illustrated in Fig. 8.22, the gNB can choose the type of the first slot, that is, mini-slot based on LBT/CCA success location and slot boundary, and then select the type of the following slots with a larger size. The type of the last slot(s) is chosen according to the remaining time within the MCOT. In the example shown in Fig. 8.22, the remainder of the MCOT is not enough for a normal slot, thus two mini-slots are allocated [17,28].

In the downlink, because a CORESET can be configured to start at any symbol, gNB can start downlink transmission from the nearest symbol after a successful LBT such that the reservation signal overhead can be minimized. However, this will cause increased blind detection complexity for the UE. Therefore, NR-U would rely on an efficient mechanism for the UE to detect the beginning of a downlink transmission. In LTE-based LAA, the initial signal was discussed to facilitate the detection of downlink burst. The NR supports non-slot-based PUSCH scheduling in the uplink and the start symbol can be dynamically indicated by DCI. Therefore, the UE can transmit PUSCH starting from the indicated symbol. However, this position may not align with the nearest symbol where LBT succeeds. Consequently, more reservation signals may be needed for the uplink. Because NR already supports multiple start positions and durations, it can provide sufficient transmission flexibility for NR-U [10,33].

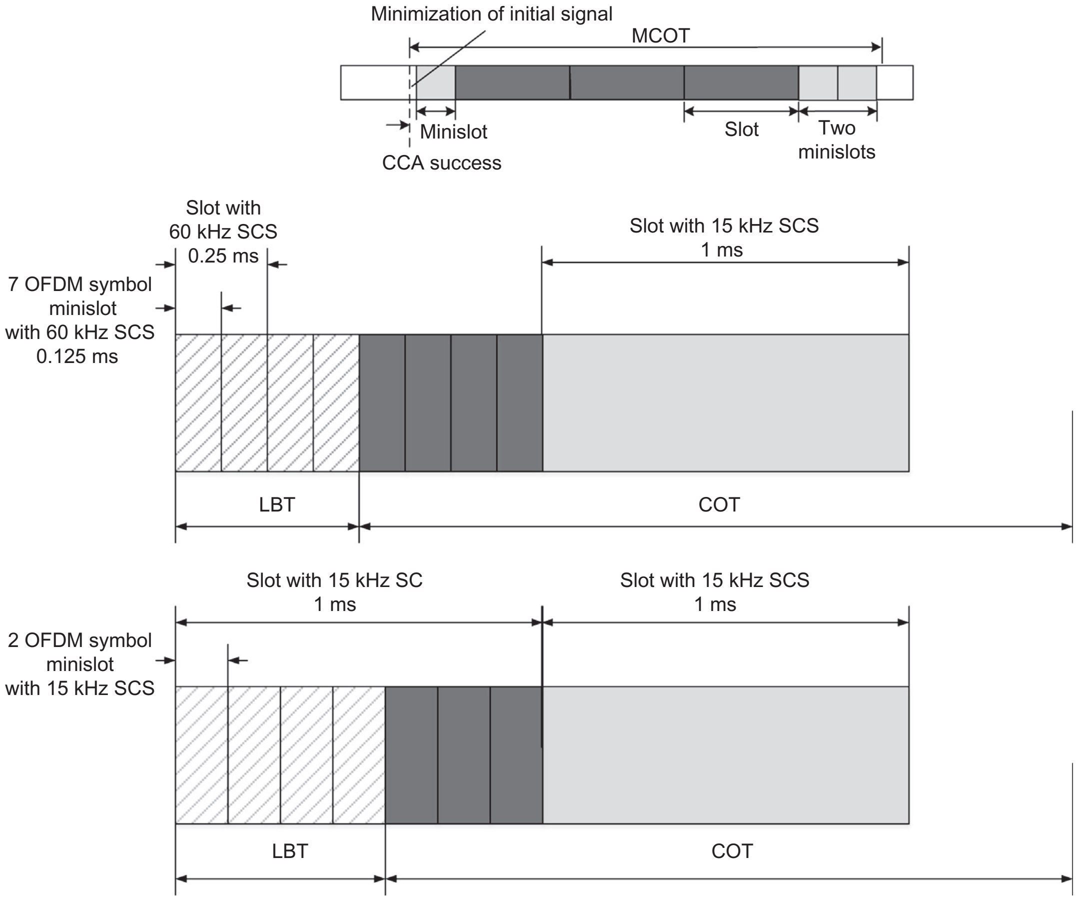

Figure 8.22
Multiple slot durations in an MCOT with different SCS [17,23].

In NR licensed operation, there are three patterns for multiplexing the SS/PBCH block and the RMSI transmissions as shown in Fig. 8.23. The number of PRBs for SS/PBCH blocks is 20 whereas the minimum number of PRBs for RMSI is 24. Using a 20 MHz bandwidth, the OCB requirement can be met if the numerology of SS/PBCH block and RMSI is set to 60 kHz. In that case, Pattern 1 can be considered for NR-U in the sub-7 GHz bands. The TDM method in Pattern 1 allows the RMSI to provide consecutive transmissions between SS/PBCH blocks over the time span of DRS. In contrast, if 30 kHz SCS is selected, the bandwidth of SS/PBCH blocks would only be about 40% of a 20 MHz. In this case, a frequency division multiplex pattern such as Pattern 2 or 3 is preferred in terms of OCB requirement. When RMSI is multiplexed with SS/PBCH blocks using Pattern 2 or 3, the RMSI may not completely fill the gaps between the SS/PBCH block transmissions.

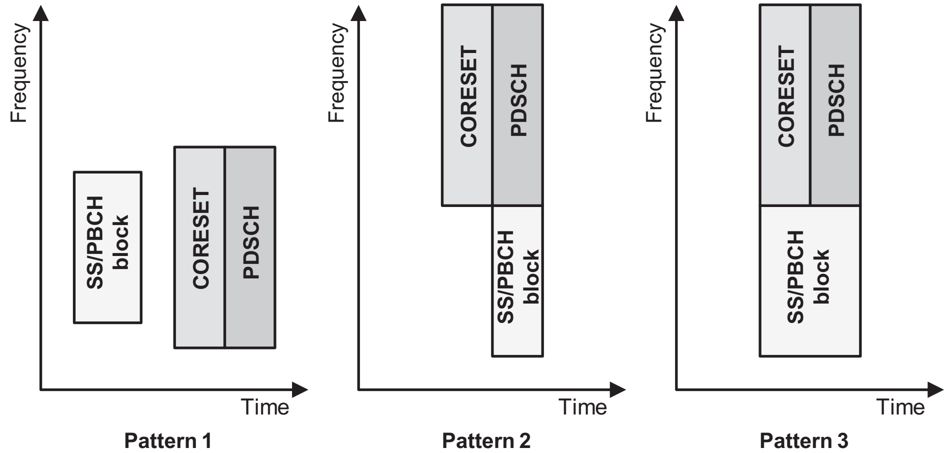

Figure 8.23
Multiplexing patterns of SS/PBCH and RMSI transmission [33].

In NR-U, because a channel occupancy time can start at any time, the UE would need to perform frequent PDCCH monitoring, even when there is no downlink transmission intended for it. To solve this issue, a wake-up signal may be designed for NR-U to wake up the UE only when necessary. The transmission of a wake-up signal is also subject to LBT. To reduce the LBT overhead, the wake-up signal can be embedded in an existing signal such as DRS that is transmitted periodically, resulting in significant UE power saving while maintaining low signaling overhead.

Similar to LTE, NR supports SRS-based frequency-selective scheduling and periodic/aperiodic SRS transmission. NR also supports SRS-based downlink beamforming and semi-persistent SRS transmission, which are not supported in LTE. In NR-U, the transmission time of the SRS resource as well as the configuration of SRS resource and resource mapping adapt to LBT and channel availability. Due to the uncertainty of channel availability, periodic SRS would not be feasible. The aperiodic SRS which is triggered by DCI has more flexibility for NR-U operation. The SRS transmission should also meet the OCB requirements; thus NR-U can only support wideband and BWP/subband SRS transmission.

In LTE-based LAA revisions, downlink and uplink transmissions start and end at certain points. More specifically, using frame structure type 3, a downlink or uplink transmission can start at slot boundaries. Because LBT may end at any time which is not necessarily aligned with the symbol boundaries, the interval between the end of LBT and the start of a PDCCH/PUSCH transmission may be wasted. The partial ending subframe reduces overhead by defining more ending points, that is, OFDM symbol positions 2, 5, 8, 9, 10, 11, and 13 for the downlink and 6, 12, and 13 for the uplink can be used as partial subframe ending

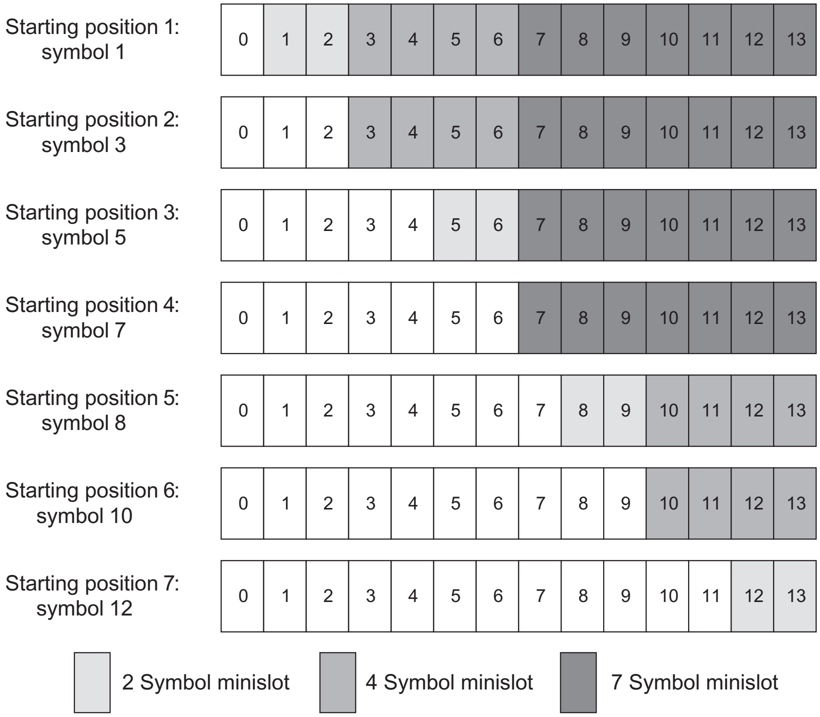

Figure 8.24
Flexible starting point with nonuniform minislot patterns [33].

points. The NR-U provides more frequent start/end points than LTE-based LAA allowing more flexible transmission as shown in Fig. 8.24.

As we mentioned earlier, LBT is a spectrum sharing mechanism that can operate across different RATs. However, it suffers from the hidden node and the exposed node problems. These issues arise when the coverage of the nodes in a network are different. The problem worsens when the sensing and transmit coverages are different. This may occur when an omnidirectional antenna pattern is used for carrier sensing whereas a directional antenna (or array) pattern is used for transmission, resulting in a higher node exposure likelihood. In the example depicted in Fig. 8.25, device A senses the carrier using omnidirectional antenna pattern and overhears the transmission from device C to D. Device A subsequently refrains from transmitting to its targeted receiving device B, which is unnecessary because the transmission from A to B using highly directional beams does not interfere with the transmission from C to D. If the direction of the communication is known, directional carrier sensing may be useful; however, this would create a different problem as shown in Fig. 8.25. The effects of directionality on carrier sensing and transmission are studied in NR-U to ensure optimal system operation and performance [34].

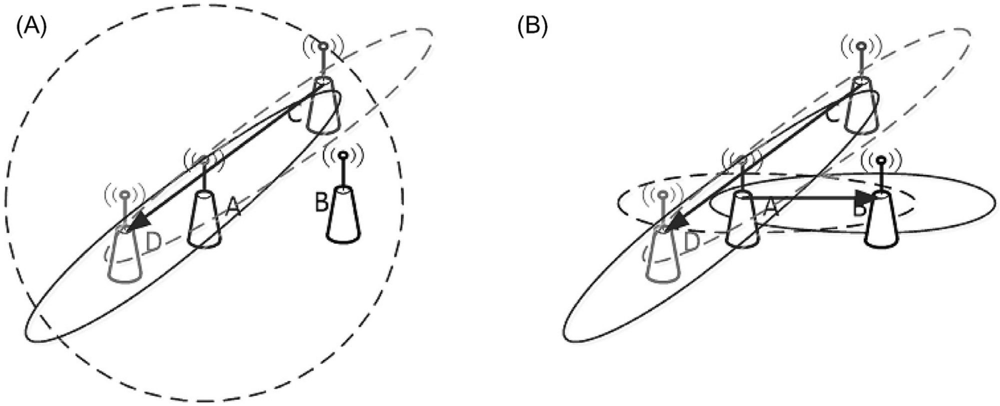

Figure 8.25
(A) Omnidirectional carrier sensing. (B) Two simultaneous directional links [34].

The NR supports CSI-RS with 1, 2, and 4 OFDM symbols and up to 32 antenna ports. It further supports periodic, aperiodic, and semi-persistent CSI-RS transmission patterns. The CSI-RS can be used for RRM measurement in the connected mode for mobility, the RSRP measurement for beam management, and CSI measurement for scheduling. The CSI-RS can be transmitted in conjunction with the SS/PBCH block and/or CORESET/RMSI using time or frequency multiplexing following an LBT process. If frequency-domain multiplexing is used, a CSI-RS resource is configured on the resources that are not occupied by SS/PBCH block and CORESET. Due to the uncertainty of channel availability for transmission of CSI-RS and the corresponding measurement report, the periodic CSI measurement and report is not feasible. Furthermore, the interference condition in the unlicensed spectrum may fluctuate severely and is unpredictable due to the larger delays between the measurement and the report as well as beamforming-based transmission.

In LTE-based eLAA, block interlaced frequency division multiple access (B-IFDMA) was introduced in the uplink transmission to ensure compliance with OCB and maximum PSD requirements while maintaining a transmit power level that can support the desired cell coverage. In NR-U, given similar regulatory requirements, the B-IFDMA serves as the baseline design for the uplink transmission. NR supports a large number of channel bandwidth combinations and subcarrier spacings, which makes the realization of a unified B-IFDMA design very challenging. A typical B-IFDMA design can be characterized by three parameters: the number of subcarriers per block N_{sc}, number of blocks per interlaces L, and number of interlaces per symbol N as illustrated in Fig. 8.26. In LTE-based eLAA, $N_{RB} = 100$ and with RB-based interlaced design, $N_{sc} = 12, L = 10$, and $N = 10$. The set of subcarriers S_n allocated for a specific interlace n can be represented as $S_n = \{N_{sc}(Nl + n) + m | 0 \leq m < N_{sc}, 0 \leq l < \lfloor N_{RB}/N \rfloor\}$. Note that it is not always possible to

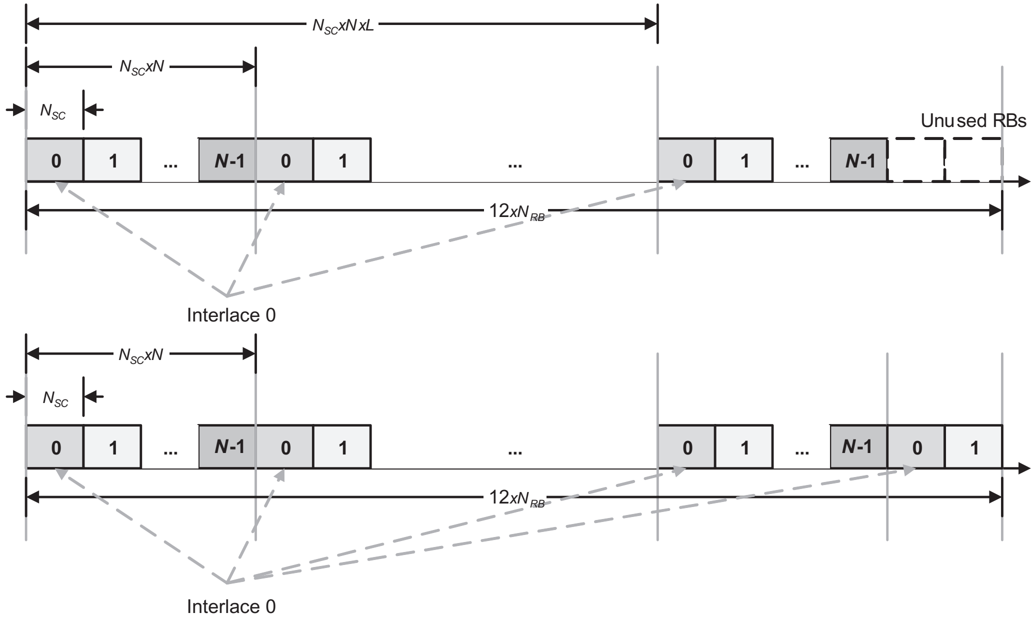

Figure 8.26
B-IFDMA design parameters and various design options [35].

divide N_{RB} by N. As an example, in NR, for a channel bandwidth of 20 MHz and subcarrier spacing of 15 kHz, $N_{RB} = 106$, and if the LTE-based eLAA parameters are maintained, then six RBs will not be used by any interlace. To avoid resource wastage, one can assign the remaining blocks to some of the interlaces. For example, if we assign R remaining blocks to the first R interlaces, then the set of subcarriers S'_n allocated for a specific interlace n can be represented as $S'_n = \{N_{sc}(Nl + n) + m | 0 \leq m < N_{sc}, 0 \leq l < (N_{RB} - n - 1)/N\}$. In this case, the number of blocks per interlace is a function of n as shown in Fig. 8.26. To meet the OCB requirement, one can design interlaces such that all interlaces occupy channel bandwidths larger than what the minimum OCB requires. In that case, the interlace parameters N_{sc}, L, and N need to be carefully chosen. In particular, assuming nominal channel bandwidth B and subcarrier spacing Δf, the minimum normalized OCB among all interlaces is given by $B_{\min} = N_{sc}\left(\left[\lfloor 12N_{RB}/(N_{sc}N)\rfloor - 1\right]N + 1\right)\Delta f / B$. As an example, in LTE-based eLAA, $\Delta f = 15$ kHz and $B = 20$ MHz, thus $B_{\min} = 0.819$, which indicates that eLAA interlace scheme can only satisfy 80% of the minimum OCB requirements. If we consider an NR numerology with $\Delta f = 60$ kHz, $B = 20$ MHz, and $N_{RB} = 24$ and if we adopt RB-based interlace $N_{sc} = 12$ to satisfy 80% of the minimum OCB requirements, the maximum number of permissible interlaces would be $N = 2$. For some NR bandwidth and SCS combinations, due to regulatory requirements and design constraints, the number of interlaces available

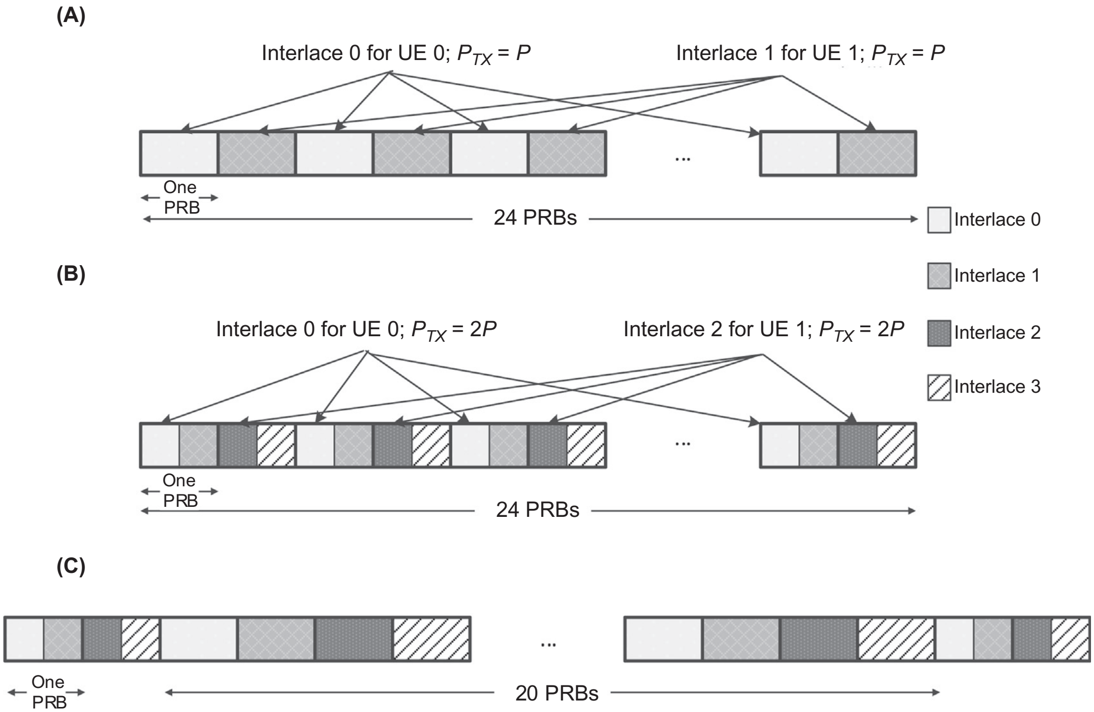

Figure 8.27

RE-group-level interlace design [35]. (A) Uniform RB level interlace. (B) Uniform RE group level interlace. (C) Nonuniform RE-group level interlace.

per symbol can be very limited; in such cases, RE-group-level interlace schemes may be utilized (see Fig. 8.27).

In Rel-15 NR, five PUCCH formats are defined, where PUCCH formats 0 and 2 are short PUCCH formats which occupy up to two OFDM symbols; PUCCH formats 1, 3, and 4 are long PUCCH formats which occupy between 4 and 14 OFDM symbols. For PUCCH formats 0 and 1, the number of UCI bits is 1 or 2, whereas, for PUCCH formats 2, 3, and 4, the UCI bits can be very large. For PUCCH formats 2 and 3, the maximum number of occupied PRBs is 16, whereas PUCCH formats 0, 1, and 4 use only one PRB. Considering the use of LBT and the regulatory requirements on OCB, NR-U makes special considerations about UCI payload size and transmission efficiency as well as UE multiplexing capacity. To overcome the uncertainty of LBT and to improve the spectral efficiency in the unlicensed band, the network may schedule uplink transmission of multiple UEs within the same channel occupancy time. However, due to the OCB requirement, the number of interlaces per symbol may be limited. As described earlier, a larger SCS value leads to a more restrictive interlace design.

8.2 Network Architecture and Protocol Aspects

In the previous section, we described the prominent methods that cellular industry has considered for access to the unlicensed spectrum, among which LWA is the only scheme that has network architecture implications that will be discussed in this section. The LWA has been supported in 3GPP specs since Rel-13, wherein a UE in RRC_CONNECTED state is configured by the eNB to utilize radio resources of LTE and Wi-Fi. Two scenarios are supported depending on the backhaul connection between LTE and Wi-Fi namely non-co-located LWA scenario for a non-ideal backhaul and co-located LWA scenario for an ideal/internal backhaul. The overall architecture for the non-co-located LWA scenario is illustrated in Fig. 8.28, where the Wi-Fi Termination (WT) terminates the Xw interface for Wi-Fi.

In LWA, the radio protocol architecture that a particular bearer uses depends on the LWA backhaul scenario and the way the bearer is set up. The LWA supports two bearer types: (1)

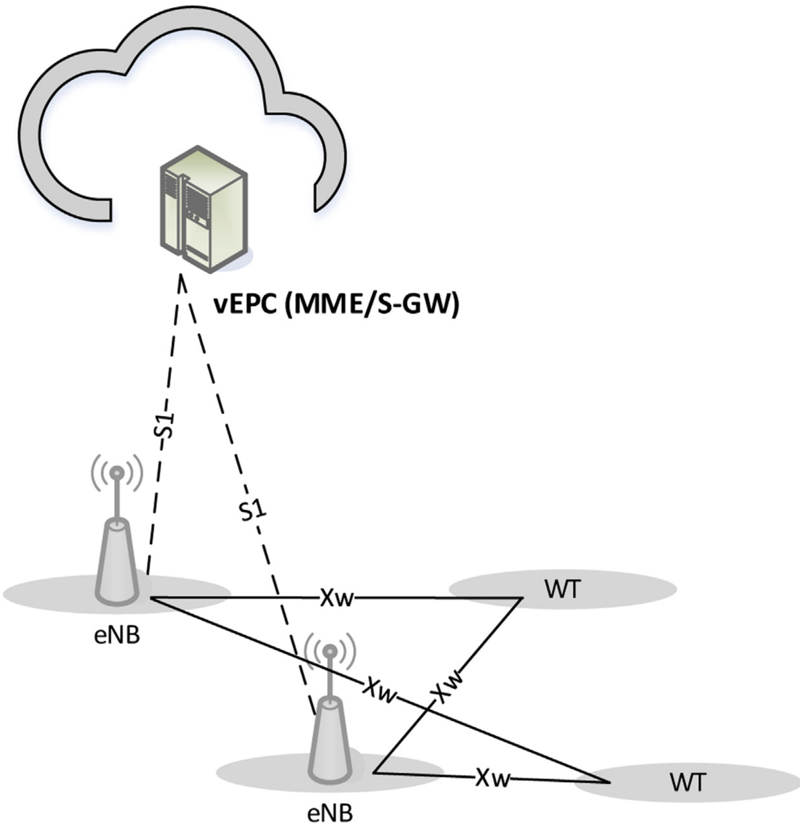

Figure 8.28
Non-co-located LWA architecture [5].

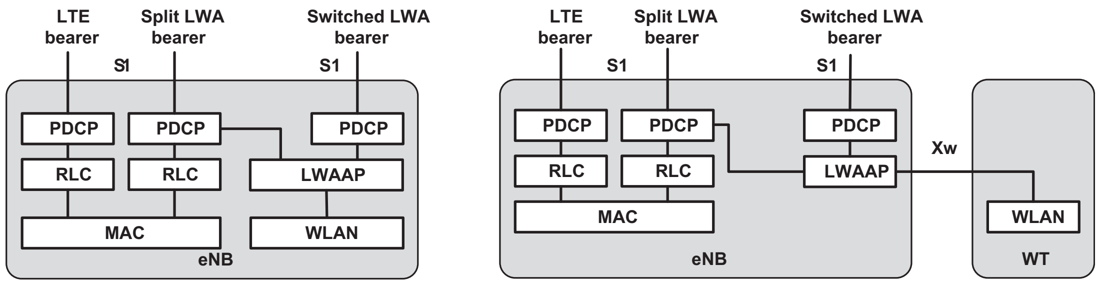

Figure 8.29
LWA radio protocol architecture for the colocated and non-co-located scenarios [5,7].

split LWA bearer and (2) switched LWA bearer. These two bearer types are depicted in Fig. 8.29 for the co-located and the non-co-located scenarios. In the non-co-located LWA scenario, the eNB is connected to one or more WTs via Xw interface. In the co-located LWA scenario, the interface between LTE and Wi-Fi is implementation specific. For LWA, the only required interfaces to the core network are S1-U and S1-MME which are terminated at the eNB. The Wi-Fi has no core network interface.

In the downlink and for the PDUs that are sent over the Wi-Fi link, the LTE-Wi-Fi aggregation adaptation protocol (LWAAP) entity generates an LWAAP PDU (i.e., a PDU with data radio bearer (DRB) ID generated by LWAAP entity for transmission over Wi-Fi) containing a DRB identity and the WT. An LWA UE determines that the received PDU belongs to an LWA bearer and uses the DRB identity to determine to which LWA bearer the PDU belongs to. In the uplink and for the PDUs sent over Wi-Fi, the LWAAP entity in the UE generates LWAAP PDU containing a DRB identity.

The LWA supports split bearer operation where the PDCP sublayer handles sequential delivery of upper-layer PDUs based on the reordering procedure introduced for dual connectivity. An LWA UE may be configured by the eNB to send PDCP status report or LWA status report in cases where feedback from WT is not available. Note that only RLC AM and RLC UM can be configured for an LWA bearer. The LTE RAN does not simultaneously configure LWA with dual connectivity, LWIP, or RAN-controlled LTE-Wi-Fi interworking for the same UE. If LWA and RAN-assisted Wi-Fi interworking are simultaneously configured for the same UE in RRC_CONNECTED, the UE only utilizes LWA. For LWA bearer, if the data available for transmission is greater than or equal to a threshold configured by LTE RAN, the UE decides which PDCP PDUs are sent over Wi-Fi or LTE links. If the data available is below the threshold, the UE transmits PDCP PDUs on LTE or Wi-Fi as configured by LTE RAN. For each LWA DRB, LTE RAN may configure the IEEE 802.11 access category value to be used for the PDCP PDUs that are sent over Wi-Fi in the uplink.

In the non-co-located LWA scenario, Xw user-plane interface (Xw−U) is defined between eNB and WT. The Xw−U interface supports flow control based on feedback from WT. The flow control function is applied in the downlink when an E-UTRAN radio access bearer (E-RAB) is mapped to an LWA bearer, that is, the flow control information is provided by the WT to the eNB to control the downlink user data flow to the WT for the LWA bearer. The operation, administration and maintenance (OAM) configures the eNB with the information of whether the Xw downlink delivery status provided by a connected WT concerns LWAAP PDUs successfully delivered to the UE or successfully transferred toward the UE. The Xw−U interface is used to deliver LWAAP PDUs between eNB and WT. In an LWA architecture, the S1-U terminates at the eNB and, if Xw−U user data bearers are associated with E-RABs for which the LWA bearer option is configured, the user-plane data is transferred from the eNB to the WT using the Xw−U interface. Fig. 8.30 shows the user-plane connectivity of eNB and WT in LWA, where the S1-U terminates at the eNB and the eNB and the WT are interconnected via Xw−U.

In the non-co-located LWA scenario, Xw control-plane interface (Xw−C) is defined between eNB and WT. The application layer signaling protocol is referred to as Xw application protocol (Xw−AP). The Xw−AP protocol supports the transfer of Wi-Fi metrics from WT to eNB; LWA for a UE in ECM-CONNECTED state; establishment, modification, and release of a UE context at the WT; control of user-plane tunnels between eNB and WT for a specific UE for LWA bearers; general Xw management and error handling functions including error indication, setting up Xw, resetting Xw, and updating the WT configuration data. The eNB-WT control-plane signaling for LWA is performed through Xw−C interface. There is only one S1-MME connection per LWA UE between the eNB and the MME. The coordination between eNB and WT is performed via Xw interface signaling.

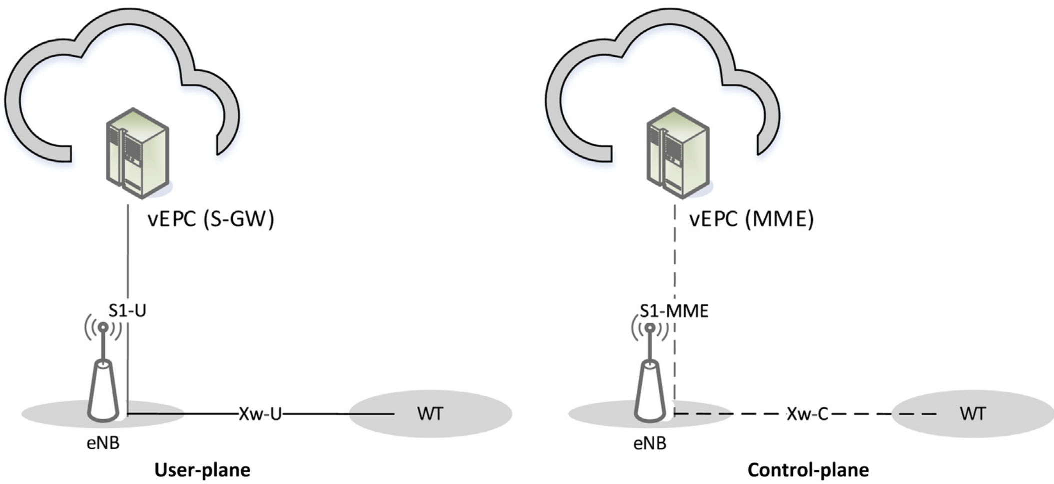

Figure 8.30
User-plane and control-plane connectivity of eNB and WT for LWA [10].

Fig. 8.30 shows control-plane connectivity of eNB and WT, where the S1-MME is terminated at the eNB and eNB and the WT are interconnected via Xw−C.

The Wi-Fi mobility set is a set of one or more Wi-Fi access points identified by their BSSID/ESSID/SSIDs (these identifiers are used to describe different sections of a Wi-Fi network), in which Wi-Fi mobility mechanisms apply while the UE is configured with LWA bearer(s), that is, the UE may perform mobility between Wi-Fi APs belonging to the mobility set without informing the eNB. The eNB provides the UE with a Wi-Fi mobility set. When the UE is configured with a Wi-Fi mobility set, it will attempt to connect to a Wi-Fi AP whose identifiers match the ones in the configured mobility set. The UE mobility relative to Wi-Fi APs not belonging to the UE mobility set is controlled by the eNB, for example, updating the Wi-Fi mobility set based on measurement reports provided by the UE. A UE is connected to only one mobility set at a time. All Wi-Fi APs belonging to a mobility set share a common WT which terminates Xw−C and Xw−U. The termination points for Xw−C and Xw−U may differ. The Wi-Fi identifiers belonging to a mobility set may be a subset of all Wi-Fi identifiers associated with the WT [5].

The UE supporting LWA may be configured by the LTE RAN to perform Wi-Fi measurements. Wi-Fi measurement object can be configured using Wi-Fi identifiers (BSSID, ESSID, or SSID), Wi-Fi carrier information and Wi-Fi band (2.4, 5, and 60 GHz). The Wi-Fi measurement reporting is triggered using RSSI measurement. A Wi-Fi measurement report contains RSSI and Wi-Fi identifier and may contain Wi-Fi carrier information, Wi-Fi band, channel utilization, station count, admission capacity, backhaul rate, and an indication whether the UE is connected to the Wi-Fi [5].

The LTE and Wi-Fi integration architecture requires Wi-Fi-specific core network nodes and interfaces (as shown by dotted lines in Fig. 8.31). However, the LWA scheme is different

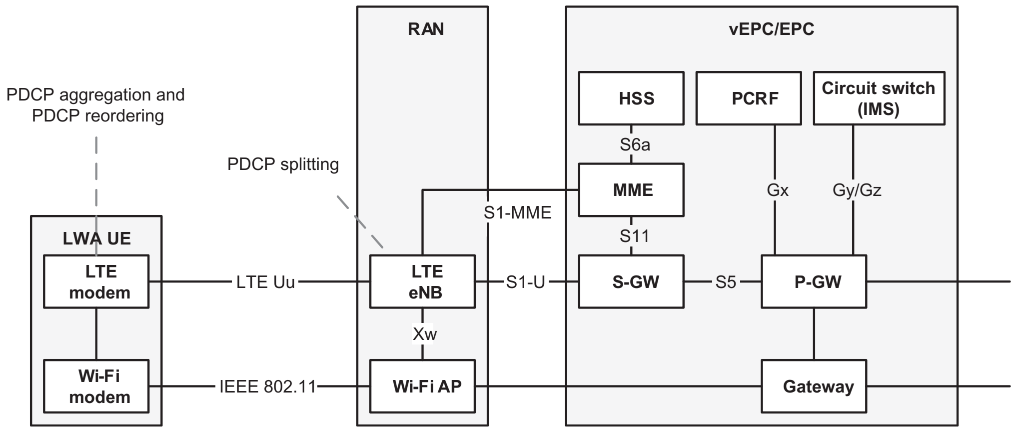

Figure 8.31
LWA network architecture (non-co-located case) [5,18].

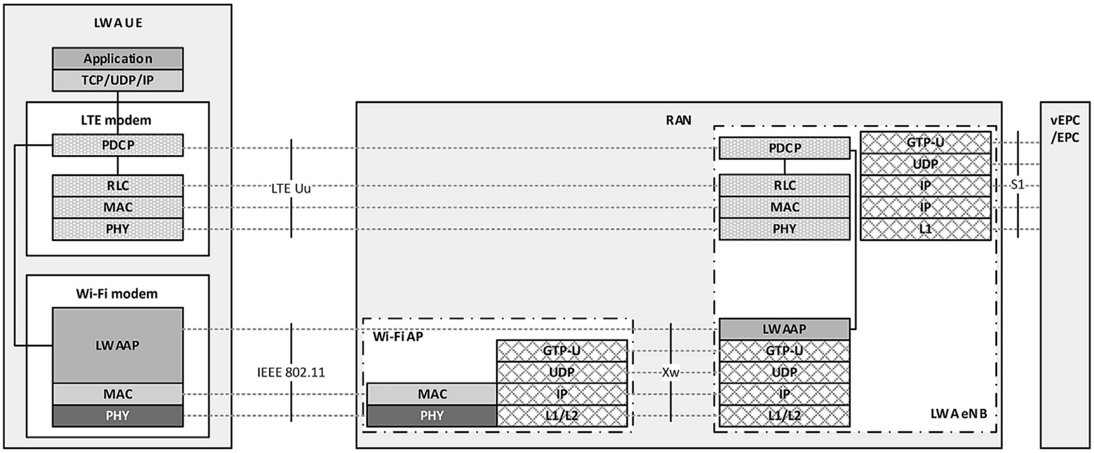

Figure 8.32
LWA protocol architecture (non-co-located case, user-plane) [5,18].

because LTE and Wi-Fi are aggregated at the radio link level. The LWA protocol architecture, data aggregation at the PDCP sublayer, signaling and interfaces between eNB and Wi-Fi AP, etc., have been specified by 3GPP and illustrated in Figs. 8.31 and 8.32.

The LWA architecture introduced a new interface Xw which was defined for communication between eNB and Wi-Fi AP, which is similar to X2, where user data is delivered through GTP tunnel, while control messages are delivered as Xw−AP messages over SCTP. Upon arriving at eNB, downlink user traffic is split in PDCP sublayer and is forwarded over LTE and Wi-Fi. Some PDCP packets are delivered via data radio bearer over the LTE radio link and other packets are delivered to Wi-Fi AP by eNB, which adds a DRB ID to the packets to indicate which DRB they belong to and delivers the LWA PDUs to Wi-Fi AP through the IP tunnel established over Xw [5]. Wi-Fi AP then sets the packet type to PDCP and forwards the LWA PDU to LWA UE over IEEE 802.11 interface. Upon receiving IEEE 802.11 frames, the LWA UE forwards the frames to LTE PDCP sublayer, if the packet type is set to PDCP. The PDCP sublayer then collects PDCP packets received from LTE and Wi-Fi that belong to the same LWA bearer by checking their DRB IDs and aggregates them through reordering. The LWA adaptation protocol supports LWA operation as shown in Fig. 8.32 [5].

8.3 Physical Layer Aspects

To support a flexible LAA operation, a new type 3 frame structure was introduced in LTE Rel-13, in which UE considers each subframe as empty unless downlink transmission is detected in that subframe. For LAA, the LBT procedure can be completed at any time and a downlink transmission may not start/end at the subframe boundary. Frame structure type 3 is applicable to LAA unlicensed carrier exclusively with normal cyclic prefix. Each radio frame is 10 ms long and consists of 10 subframes of length 1 ms. Any of these 10 subframes can be used for uplink/downlink transmission or can be empty. LAA transmission can start and end at any subframe and can consist of one or more consecutive subframes in the burst. Partial subframes are introduced by 3GPP, as part of frame structure type 3, to support LBT and for efficient use of unlicensed spectrum by LAA scheme. Partial subframe in LAA uplink burst is transmitted either from the start of the zeroth symbol or from the start of the first symbol in a subframe. The transmission can also start between the zeroth and the first symbol [1]. Therefore, the zeroth symbol in the first subframe of an LAA uplink burst can be partially filled, fully filled, or empty. The LAA uplink transmission can end either at the 12th or 13th OFDM symbol in a subframe [2]. Therefore, the last subframe in an LAA uplink transmission can be filled with 14 OFDM symbols or can be partially filled with 13 OFDM symbols. The LAA downlink transmission can start from the zeroth OFDM symbol (subframe boundary) or from the seventh OFDM symbol (second slot starting position) of a subframe [3,4]. The LAA downlink transmission can either end at the subframe boundary or at any existing downlink pilot time slot (DwPTS) symbol (in frame structure type 2). Therefore, the last subframe can be completely occupied with 14 OFDM symbols or consist of any of DwPTS symbols, that is, 3, 6, 9, 10, 11, or 12 OFDM symbols [1]. Example configurations of frame structure type 3 are shown in Fig. 8.33 [1].

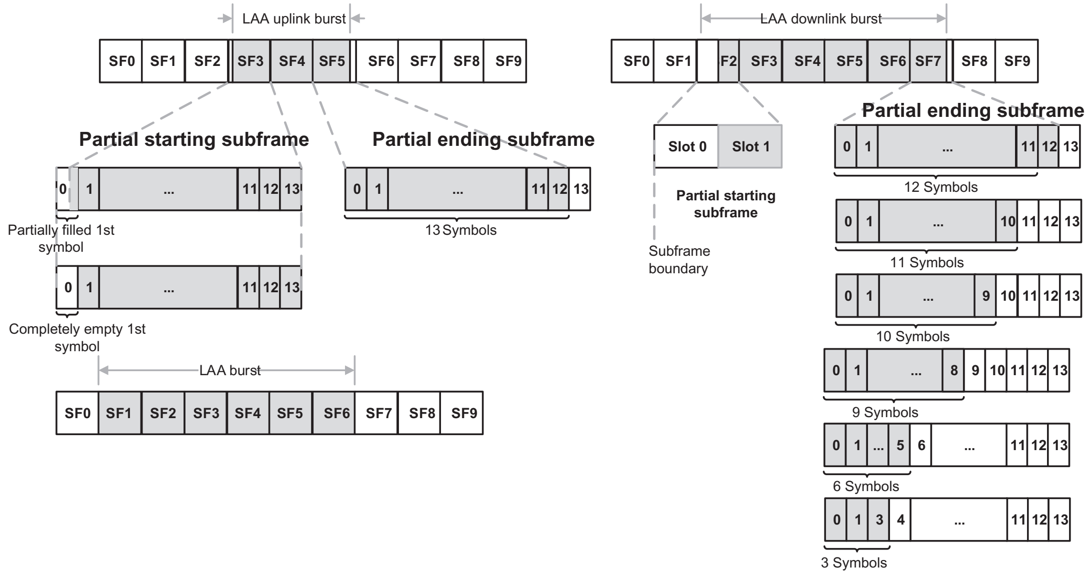

Figure 8.33
Example configurations of frame structure type 3 [1].

Cell selection and synchronization rely on the reception of the synchronization signals, that is, primary and secondary synchronization signal (PSS/SSS) as well as cell-specific reference signals (CRS). In particular, PSS/SSS can be used for physical cell identity detection, and the CRS can be used to further improve the performance of cell ID detection. These synchronization signals are further used to acquire coarse and fine time/frequency synchronization, although large time/frequency offset between two successive downlink bursts is unlikely due to multiple DRS transmission opportunities within a DRS measurement timing configuration (DMTC) occasion which has a duration of 6 ms. Therefore, the synchronization based on DRS in LAA systems can achieve reliable performance. The presence of downlink subframe must be detected by the LAA UE because the eNB does not always transmit in LAA scenarios. The exact detection method depends on UE implementation.

LTE-based LAA supports transmission modes (TMs) with CRS-based CSI feedback, including TM1, TM2, TM3, TM4, and TM8, and those with CSI-RS-based CSI feedback, including TM9 and TM10 [3]. The CSI-RS/CSI-IM for CSI measurement is present in the configured periodic CSI-RS/CSI-IM subframes within downlink transmission bursts. Similar to the legacy LTE systems, both periodic and aperiodic CSI reports are supported in LAA scenarios. Unlike the legacy LTE system where the CRS/CSI-RS transmission power, or energy per resource element, is fixed, CRS/CSI-RS transmission power on LAA SCell is only fixed within a downlink transmission burst and can vary across downlink transmission bursts. Thus, the UE should not average CRS/CSI-RS measurements across different transmission bursts. The UE could either rely on CRS detection or common control signaling to differentiate the downlink bursts. LTE supports two different scheduling approaches, namely cross-carrier scheduling and self-scheduling. With cross-carrier scheduling, the control information including scheduling indication on PDCCH and the actual data transmission on PDSCH take place on different carriers, whereas they are transmitted on the same carrier in the case of self-scheduling. Due to the uncertainty of channel access opportunities on unlicensed carriers, the synchronous uplink HARQ protocol with fixed timing relation between retransmissions was difficult to use in LAA. Thus, asynchronous HARQ protocol is used for LAA downlink and uplink. For LAA uplink, in particular, UEs would need to rely on the uplink grant from eNB for (re)transmissions.

Enhanced licensed-assisted access was introduced in 3GPP Rel-14. It defines how a UE can access 5 GHz band to transmit data in the uplink direction. Because all uplink transmissions in LTE are scheduled and controlled by the serving eNB, the channel contention between devices and the LBT scheme, which was defined in LAA for downlink operation, needed to be adapted to the uplink direction. Furthermore, the regulatory requirements for access to 5 GHz band vary in different regions. For example, ETSI requires that the OCB, defined by 3GPP as the bandwidth containing 99% of the signal power, to be between 80% and 100% of the declared nominal channel bandwidth [29]. As an initial approach, multi-cluster PUSCH transmission, which was specified in 3GPP Rel-10, was considered to fulfill this

ETSI requirement [29]. Multi-cluster PUSCH allows two clusters of resource blocks to be scheduled far enough from each other to fulfill, for example, the 80% bandwidth requirement. However, further studies in 3GPP suggested that the latter was not an efficient solution. Furthermore, the PSD limits defined for the 5G GHz band was another limitation of the multi-cluster PUSCH approach as shown in Fig. 8.34. The LTE-based eLAA supports multi-subframe scheduling, where an uplink grant can schedule PUSCH transmissions in a number of consecutive subframes ranging from two to four subframes. It further supports DCI formats 0A and 4A for single subframe scheduling and DCI formats 0B and 4B for multi-subframe scheduling for single-layer and multi-layer PUSCH transmissions, respectively (see Fig. 8.35).

As an example, the 10 dBm/MHz defined by the ETSI over 5150−5350 MHz frequency range is shown in Fig. 8.34, where ETSI allows a PSD of 17 dBm/MHz (over 5470−5725 MHz) if TPC can be applied [29]. The US FCC defines 11 dBm/MHz PSD for 5150−5350 MHz frequency range. As a result, 3GPP adopted the principle of B-IFDMA

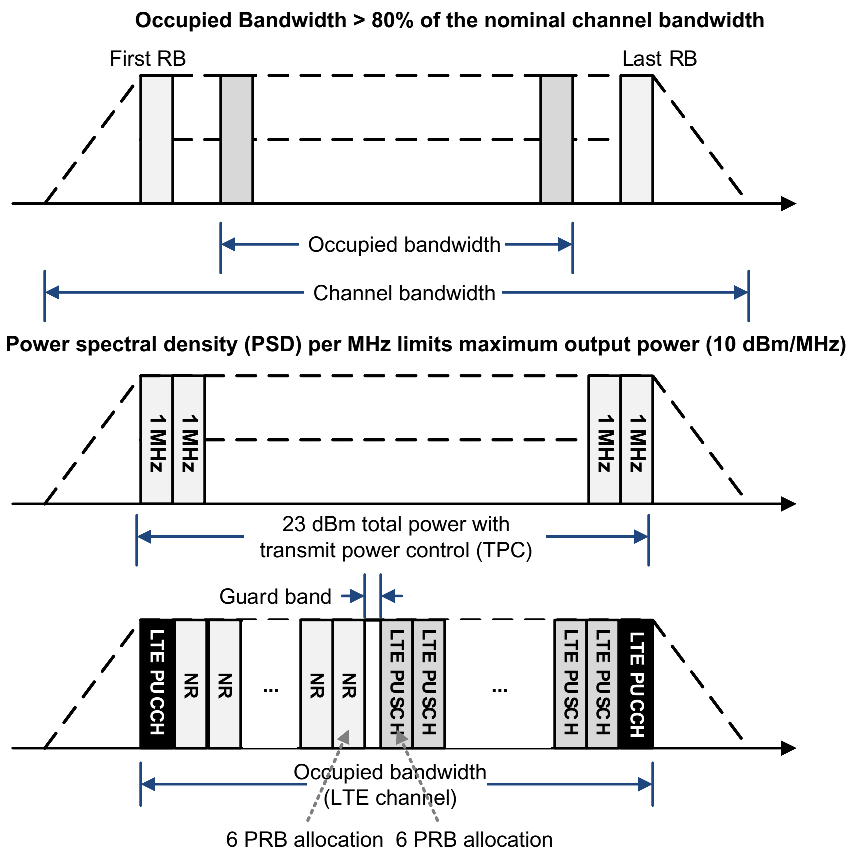

Figure 8.34
ETSI requirements for transmission 5 GHz band [22,27,29].

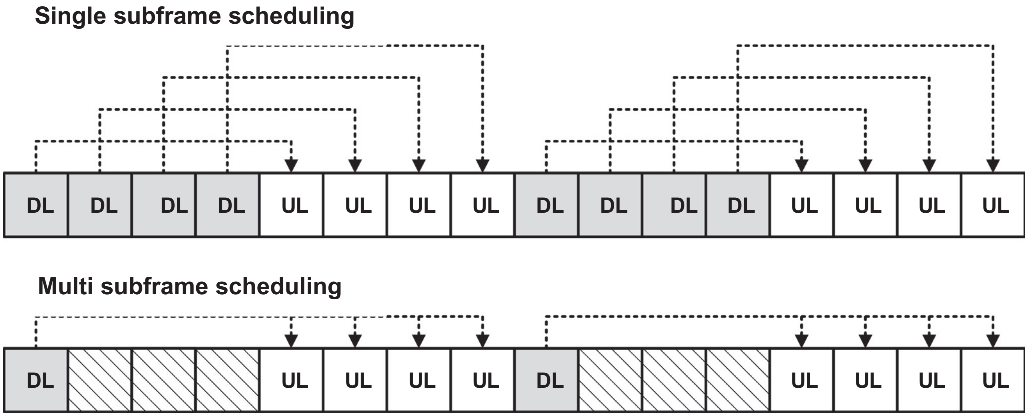

Figure 8.35
Multi-subframe scheduling versus single subframe scheduling [23].

for eLAA. The available number of resource blocks is organized in interlaces that are equally spaced in the frequency domain. A UE can now transmit on one or multiple interlaces. Similar to LTE uplink transmissions, the total number of allocated resource blocks must be multiples of 2, 3, and 5 to minimize the complexity of the DFT precoding. To incorporate this specific access mode into the standard, 3GPP Rel-14 specified a new uplink resource allocation type 3 that is only applicable for LAA. As a result, two new scheduling grants (DCI format 0A/0B and 4A/4B) were introduced. A DCI transports downlink, uplink or sidelink scheduling information, requests for aperiodic CQI reports, LAA common information, or uplink power control commands for one cell and one RNTI. The RNTI is implicitly encoded in the CRC. DCI formats 0A and 4A schedule single subframes for single antenna (0A) and multi-antenna (4A) transmission, whereas DCI formats 0B and 4B allow scheduling of up to four consecutive subframes for SISO and MIMO, respectively. These new uplink grants provide the UE with a resource indication value RIV that is either 5 or 6 bits (5 bits for 10 MHz channel and 6 bits for 20 MHz channel). The RIV represents a start value RB_{start} and the actual number of allocated resource blocks L. For a 20 MHz LTE channel, corresponding to 100 resource blocks, there are 10 interlaces with 10 RBs/interlace. Interlace 0 contains resource blocks $(0, 10, 20, 30, 40, 50, 60, 70, 80, 90)$ as shown in Fig. 8.36. If the UE transmits on 4 out of the 10 available RBs per interlace $L = 4$, then the RIV is calculated as $RIV = N(L-1) + RB_{start}$. With $N = 10$, RB_{start} can have a value between 0 and 6 and RIV can be between 30 and 36. The RIV is signaled via DCI to the UE. In addition to this and other information, the DCI format also includes the method on how to access the channel, that is, how to perform LBT in the uplink. As shown in Table 8.3, there are two channel access types defined for eLAA, whose usage is signaled with the uplink scheduling grant (DCI formats 0A, 0B, 4A, 4B). The type 1 channel access procedure is identical to the procedure for LAA. The difference is that there are separate

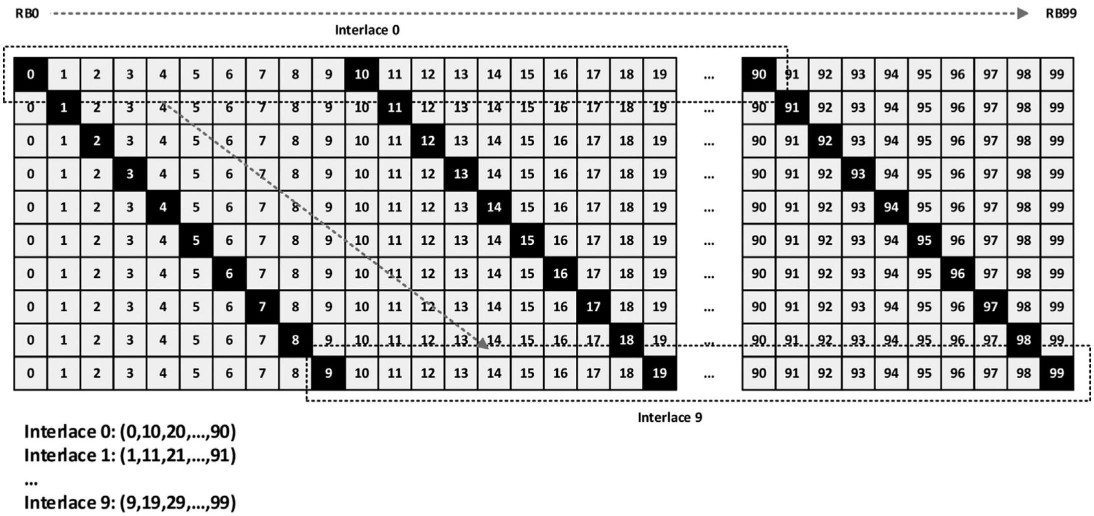

Figure 8.36
eLAA interlaces for 20 MHz LTE channel [22].

channel access priority classes defined for the uplink. Type 2 is a procedure similar to transmitting DRS in the downlink. After sensing that the channel is idle for 25 μs, the device can start its PUSCH transmission [22].

It must be noted that DCI format 0A is used for the scheduling of PUSCH in an LAA SCell and DCI format 0B is used for the scheduling of PUSCH in each of the multiple subframes in an LAA SCell. Furthermore, DCI format 1C is used for very compact scheduling of one PDSCH codeword, notifying multicast control channel change, notifying single-cell multicast control channel change and direct indication, reconfiguring TDD, and LAA common information, whereas DCI format 4 is used for the scheduling of PUSCH in an LAA SCell with multi-antenna port transmission mode. DCI format 4B is used for the scheduling of PUSCH with multi-antenna port transmission mode in each of the multiple subframes in an LAA SCell.

The LTE-based LAA supports two alternative approaches to multi-carrier LBT. In the first approach, the eNB is required to designate a carrier requiring LBT with random backoff and the eNB can sense other configured carriers with single interval LBT, only if the eNB completes the LBT with random backoff on the designated carrier. In the second approach, the eNB performs LBT with random backoff on more than one unlicensed carriers and can transmit on the carriers that have completed the LBT with potential self-deferral to align transmissions over multiple carriers. An LTE eNB can access multiple carriers on which LAA SCell(s) transmission(s) are performed using either Type A or Type B procedures as follows [4]:

- *Type A multi-carrier access procedure*: The eNB performs channel access on each carrier $c_i \in C$, where C is a set of carriers on which the eNB intends to transmit and

$i = 0, 1, \ldots, N_{carrier} - 1$ is the carrier index. The eNB transmission may include PDSCH/PDCCH/ePDCCH on an LAA SCell(s) carrier(s), after sensing the channel to be idle during the slot durations of defer period T_{defer} and after the counter N is initialized and adjusted by sensing the channel for additional slot duration(s). The counter N is determined for each carrier c_{i} and is denoted as N_{c_i}. In Type A1, the counter N is independently determined for each carrier. If the absence of another technology sharing the carrier cannot be guaranteed over a long period of time, and when the eNB stops transmission on any carrier $c_j \in C \forall c_i \neq c_j$, it can continue to decrement N_{c_i} when idle slots are detected either after waiting for a duration of $4T_{slot}$ or after reinitializing N_{c_i}. In Type A2, the counter N_{c_j} is determined for the carrier $c_j \in C$, where c_j is the carrier that has the largest contention window CW_p value. For each carrier c_i, $N_{c_i} = N_{c_j}$. When the eNB stops transmission on any carrier for which N_{c_i} is determined, it reinitializes N_{c_i} for all carriers.

- *Type B multi-carrier access procedure*: A carrier $c_j \in C$ is selected by the eNB by randomly choosing c_j from C before each transmission on multiple carriers $c_i \in C \forall i = 0, 1, \ldots, N_{carrier} - 1$, or the eNB selects c_j less frequently, where C is a set of carriers on which the eNB may transmit. To transmit on a carrier $c_i \neq c_j \forall c_i \in C$, the eNB performs carrier sensing for a minimum sensing interval $T_{mc} = 25\ \mu s$ prior to transmitting on carrier c_j, and it may transmit on carrier c_i immediately after sensing the carrier c_i to be idle for at least the sensing interval T_{mc}. The carrier c_i is considered to be idle for T_{mc} if the channel is sensed to be idle during all time intervals in which such idle sensing is performed on carrier c_j in a given time interval T_{mc}. The eNB will not continuously transmit on a carrier $c_i \neq c_j \forall c_i \in C$ for a period exceeding T^p_{MCOT}, where the value of the latter parameter is determined using the channel access class used for carrier c_j. In Type B1, a single CW_p value is maintained for the set of carriers C. For determining CW_p for performing channel access on carrier c_j, if at least 80% of HARQ feedback corresponding to PDSCH transmission(s) in reference subframe k of all carriers $c_i \in C$ are determined as NACK, then CW_p is increased for each priority class $p \in \{1, 2, 3, 4\}$ to the next higher permissible value. In Type B2, a CW_p value is maintained independently for each carrier $c_i \in C$. For determining N_{init} for the carrier c_j, CW_p value of carrier $c_{j1} \in C$ is used, where c_{j1} is the carrier with largest CW_p among all carriers in set C.

Discontinuous transmission on an unlicensed carrier with limited maximum transmission duration has an impact on some LTE/NR essential functionalities that support AGC setting, time and frequency synchronization of the UEs, and channel reservation. Channel reservation refers to the transmission of signals by an LAA node after gaining channel access via a successful LBT operation, so that other nodes that receive the transmitted signal with energy above a certain threshold sense the channel to be occupied.

8.4 Layer 2/3 Aspects

In this section, we discuss the L2/L3 aspects and impacts of unlicensed band operation in LTE and NR-based systems. The uncertainty of the cell availability for HARQ retransmissions on unlicensed carriers would create some limitations for normal HARQ operation. The uncertainty may arise due to the LBT operation needed to acquire the channel or because the maximum transmission duration for LAA is exceeded. Fig. 8.37 illustrates an example in which the maximum transmission duration of an LAA cell has been reached before the third retransmission of a HARQ process can be performed. There are two ways to address this issue. One approach is to keep the HARQ retransmissions on the same LAA cell or to ensure that the HARQ process is completed within the maximum transmission duration of an LAA cell as shown in Fig. 8.37. A new HARQ process is started when the LAA cell reacquires the channel after an LBT operation. Alternatively, a retransmission can be delayed until the LAA cell acquires the channel again. The RLC retransmission may be invoked if HARQ transmission is not successfully completed. Another alternative would be to move HARQ retransmissions to another cell (note that each carrier in the carrier aggregation framework is referred to as a cell). The retransmission may also be performed via another cell which would be either the PCell or another SCell. This would change the baseline LTE HARQ protocol as it may be linked to two or more cells.

In synchronous HARQ, the UE identifies the HARQ process that is associated with the current transmission time interval (TTI). Depending on whether spatial multiplexing is used, each TTI has one or two associated HARQ processes, and for the identified HARQ

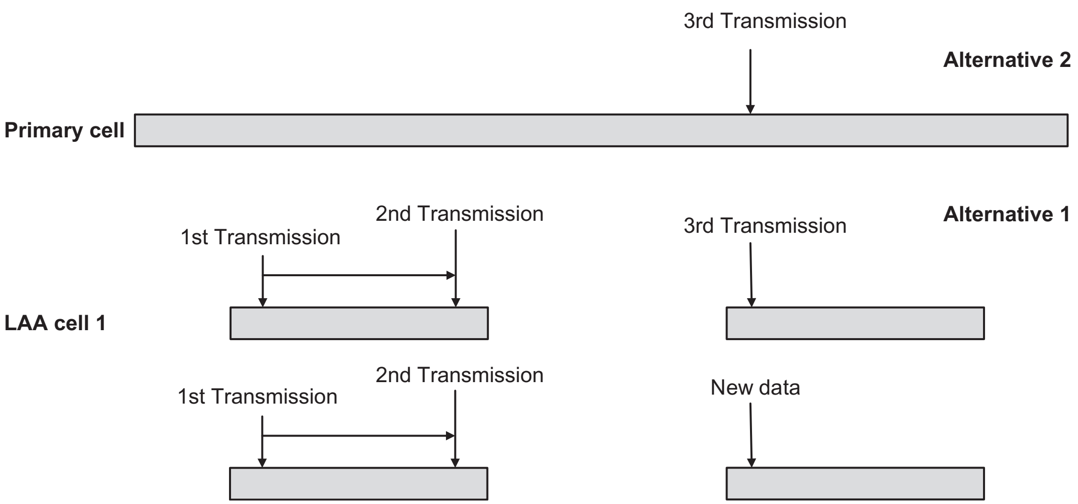

Figure 8.37
Illustration of HARQ issue in LAA cell [9,12].

processes, the UE will perform a (re)transmission. The association between TTIs and HARQ processes relies on uplink HARQ being synchronous and is derived from the timing relation. If there has been an initial transmission in a certain subframe for a certain HARQ process, then $T_{round\text{-}trip}$ later, the same HARQ process is considered for retransmission. In LTE, the UE receives uplink HARQ feedback from the eNB on PHICH. PHICH received in subframe k relates to the transmission in the subframe $k-4$. If the UE receives NACK on PHICH (but does not receive a grant), a non-adaptive retransmission is automatically triggered. LTE-based LAA uses asynchronous HARQ in the uplink. To enable asynchronous HARQ, the eNB needs to know the HARQ process that the UE is using when performing a transmission/retransmission to correctly choose the soft-buffer where the received transmission should be combined. Hence, the eNB needs to indicate to which HARQ process a grant is related and the redundancy version that should be used so that the UE uses the correct HARQ process with the correct redundancy version when performing a transmission or retransmission. Therefore, with the uplink asynchronous HARQ protocol, all transmissions or retransmissions are scheduled via (e)PDCCH. The process index is indicated in the HARQ process index field in the uplink grant. For synchronous uplink HARQ, the number of HARQ processes is not explicitly specified. Instead, the supported number is derived from the HARQ timing. For asynchronous uplink HARQ, a maximum number of HARQ processes may need to be specified. The exact number of uplink HARQ processes in the eNB may be left to implementation [12].

In synchronous uplink HARQ, the UE can expect to receive uplink grants at a specified time as the HARQ process follows a fixed pattern. It should be noted that the UE monitors (e)PDCCH once in every HARQ RTT even if the UE has received ACK in PHICH. With asynchronous uplink HARQ, the UE does not know when to expect grants as the eNB may send them at any time. In addition, if HARQ buffer is not flushed, the UE would never stop monitoring (e)PDCCH according to the current mechanism. Therefore, with asynchronous uplink HARQ, the DRX behavior needs to be modified. In carrier aggregation, the same DRX operation applies to all configured and activated serving cells (i.e., identical active time for PDCCH monitoring). In other words, a common DRX is applied to all the serving cells. The difference in the case of LAA is that due to LBT there is no guarantee that the channel is obtained for scheduling the UE at the exact moment desired by the eNB. In addition, even if CCA succeeds, the eNB transmitter can only occupy the channel for a limited duration due to limited maximum transmission duration requirement. This means that the DRX timers (on-duration, inactivity timer) should be long enough or DRX cycles should be short enough to allow time for obtaining access to the channel.

In LAA, there are scenarios where multiple operators may operate in the same frequency channel. If these operators do not coordinate the allocation of physical cell identifier (PCI) values across their cells, it may lead to PCI confusion or PCI collision cases. PCI confusion refers to the case where a UE discovers and configures the LAA cell of another operator with the same PCI value as its own operator. PCI collision concerns a UE that is in the coverage area of two (or more) cells which have the same PCI value where the cells belong to different operators. If the same PCI value is used for cells on the same carrier frequency in the same area, PCI confusion or collision may occur. In LTE and NR, the number of PCIs is limited to 504 and 1008, respectively. If operators do not coordinate PCI assignment in their cells, the probability of PCI confusion or collision depends on the number of LAA cells of other operators the UE can find in the PCell coverage area, increasing the risk of collision when there is a dense deployment of LAA cells in a large PCell coverage area. PCI collision will happen with a lower probability than PCI confusion because PCI collision happens when the coverage areas of two cells with the same PCI partially overlap. Considering the LTE requirement for carrier aggregation where the UE is only required to handle a maximum timing difference of approximately $30\,\mu s$ between the PCell and an SCell, the UE may not be able to receive anything from the other operator's LAA cell, if the downlink signal of that cell arrives later than $\pm 30\,\mu s$ of the UE's PCell. The probability that the other operator's LAA cell overlaps with the UE's PCell is 6% assuming random timing of cells. Furthermore, for self-scheduling, the UE will not decode downlink assignments of the other operator's cell unless the downlink transmissions are scrambled with a C-RNTI value matching the C-RNTI assigned to the UE. Considering that there are 65536 C-RNTIs (16-bit values), if the other operator serves 20 UEs in a cell, the probability that the same C-RNTI is used is roughly 0.03%. Therefore, the probability that the UE can decode a downlink message from another operator's LAA cell is 0.0018% [14,20].

In the event of a PCI confusion when self-scheduling from the LAA cell, the probability that the UE could decode downlink is negligible (0.0018% in the scenario described earlier). However, in case of cross-carrier scheduling from the PCell, the UE would never be able to decode the downlink data for which the UE has received a downlink assignment as the data is sent in another cell. In the uplink, the UE will not be able to acquire uplink synchronization and would therefore not be able to transmit uplink traffic in the other operator's cell. However, it may send unnecessary random-access preambles to another operator's LAA cell (e.g., if it receives a PDCCH order from the PCell). It is expected that the eNB can detect PCI confusion by observing that the UE is reporting good quality for a cell, but no data communication is succeeded for this UE. The eNB can then resolve the confusion by changing the PCI for the problematic cell(s).

In the event of a PCI collision, there is a non-negligible likelihood that both LAA cells become unusable to the UEs that fall in their common coverage area. This would result in the UE not being able to receive the downlink and/or transmit in uplink while in those cells. It is also expected that in some cases, that is, not in hidden-node cases where the two cells with the same PCI are hidden from each other but are heard by the UEs, the network can detect PCI collision by listening to carriers and avoid the collision by changing the PCI values of their cells. PCI confusion and PCI collision can be avoided completely if operators coordinate the PCI values for their LAA cells. Otherwise, the probability of occurrence would be scenario dependent.

In LWA, the UE mobility is transparent to the eNB while in a Wi-Fi mobility set, that is, a group of Wi-Fi access points that are controlled by one WT logical entity. As long as the UE moves between APs of the same mobility set, it does not need to inform the eNB about its movement. When the UE leaves the mobility set, the eNB may change the access point based on the Wi-Fi measurements, thus it informs the UE of its decision.

Coexistence with other technologies is very important for LAA, and therefore accessing and using already congested frequencies/channels that are used by Wi-Fi access points and clients should be avoided. Because efficient radio resource management is critical for the overall performance of LAA scheme, LTE defines signal quality criteria such as reference signal received power [RSRP (dBm)] and reference signal received quality [RSRQ (dB)] metrics to effectively quantify the [shared] channel conditions. The RSSI serves as the key performance indicator for interference on a given carrier. To measure RSSI, the DRS needs to be present. However, because DRS is subject to LBT, any RSSI measurement report of an LAA-capable UE needs to include a time stamp indicating when the measurements were conducted. Therefore, higher layers configure an RSSI measurement time configuration (RMTC) with a measurement period [40, 80, 160, 320, or 640 ms], a subframe offset [0,. . .,639] and a measurement duration [1, 14, 28, 42, or 70 OFDM symbols]. The device averages the RSSIs over the measurement duration and conducts measurements according to the signaled periodicity. The device reports the average RSSI as well as the channel occupancy (CO), which is defined as the percentage of measured RSSI samples above a predefined threshold that is also signaled by higher layers. Both metrics provide an indication of the load and interference condition on the given LAA SCell. An example RMTC configuration with an averaging granularity of one OFDM symbol, measurement duration of 70 symbols or 5 ms with a periodicity of 40 ms, and a total measurement period comprising three measurement durations or 120 ms is illustrated in Fig. 8.38.

The Rel-16 NR-U supports 4-step and 2-step RACH procedures, where the 2-step RACH refers to the procedure that can complete contention-based RACH (CBRA) in two steps. The use of 2-step RACH may be beneficial due to less LBT impact with the reduced number of messages. The NR-U further supports contention-free RACH (CFRA) and CBRA for both 2-step and 4-step RACH. On SCells, CFRA is supported as a baseline, while both CBRA and CFRA are supported on SPCells. In the 4-step RACH procedure, the messages in time order are named as msg1, msg2, msg3, msg4, and in 2-step RACH, the messages are identified as msgA and msgB. A single RACH procedure will be used and thus multiple RACH procedures in parallel will not be supported for NR-U. As a baseline, the random-access response to msg1 will be on SPCell and msg3 is assumed to use a predetermined HARQ ID. In legacy RACH, the counters for preamble transmission and power ramping are increased with every

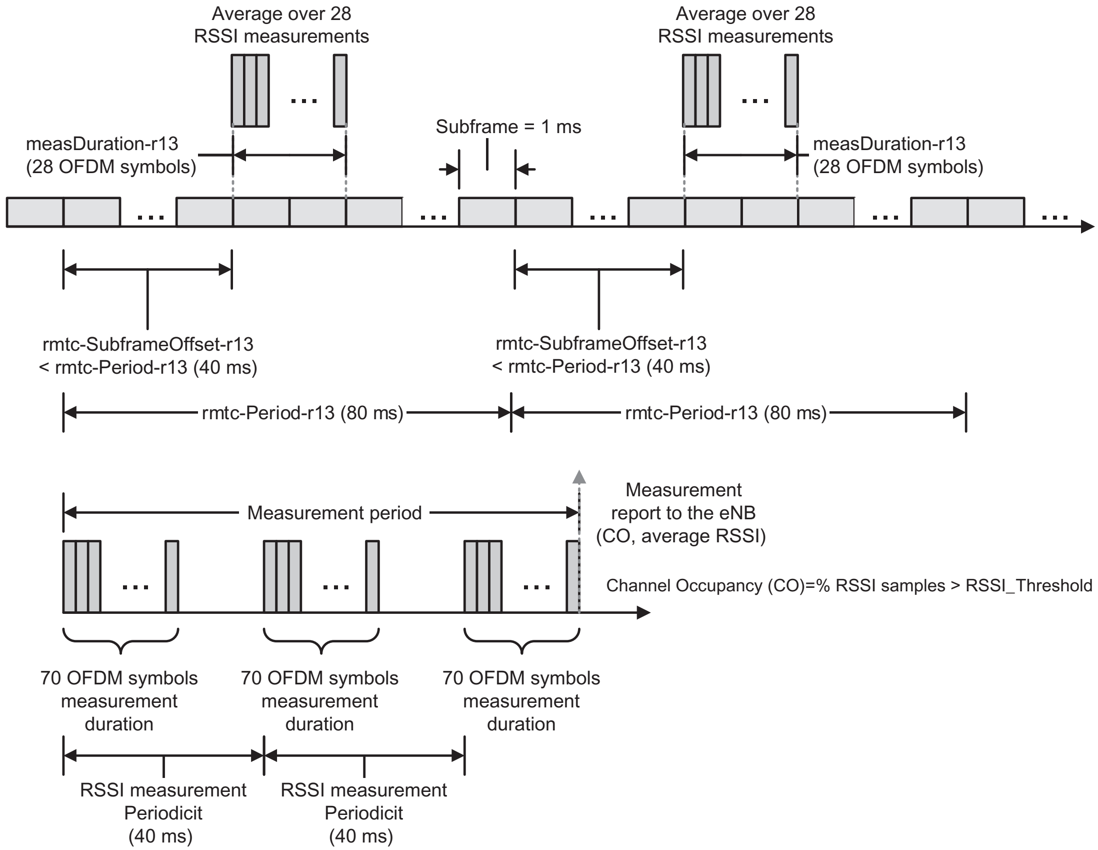

Figure 8.38
RMTC configuration for channel occupancy measurements based on R

attempt. In NR-U, power ramping is not applied when preamble is not transmitted due to LBT failure. This will require an indication from the physical layer to the MAC sublayer. In addition, ra-ResponseWindow is not started when the preamble is not transmitted due to LBT failure. It is assumed that ra-ContentionResolutionTimer may need to be extended with larger values to overcome the LBT impact. For 2-step RACH, the msgA is a signal to detect the UE and a payload while the second message is for contention resolution for CBRA with a possible payload. The msgA will include the equivalent information, which is transmitted in msg3 for 4-step RACH [12].

8.5 Implementation and Deployment Considerations

The main challenge in the implementation and use of LTE/NR in the unlicensed bands, particularly in 5 GHz band, is the coexistence with already deployed Wi-Fi networks, where LTE/

NR operation would adversely impact the performance of Wi-Fi systems, while the performance of LTE/NR would remain unchanged due to reliance of Wi-Fi systems on CSMA/CA mechanism. The issue is caused because of different channel usage and access procedures of these technologies. LTE/NR is designed to operate in the licensed bands based on the assumption that one operator has exclusive control of a given spectrum. They will continuously transmit with minimum time gap even in the absence of user traffic. LTE/NR also has an almost continuously transmitting protocol, as well as a periodically transmitting protocol to transmit a variety of control and reference signals. Wi-Fi, on the contrary, is designed to coexist with other technologies through random backoff and channel sensing. As a result, Wi-Fi users would have a slight chance to sense a clear channel and to transmit.

To ensure fair spectrum sharing and [practically] minimum inter-system interference among different wireless technologies operating in the unlicensed spectrum, 3GPP has specified a number of Wi-Fi coexistence mechanisms. These mechanisms operate in time, frequency, or power domains. In the frequency and time-domain schemes, the goal is to separate transmissions of LTE and Wi-Fi in frequency and time, respectively, while in the power domain, the goal is to adjust the output power of LTE nodes to a tradeoff between LTE throughput and opportunistic Wi-Fi transmission. Prior to any specification work on LAA, 3GPP conducted studies to investigate the feasibility of LTE operating in unlicensed bands [9]. The focus of those studies was fair sharing and coexistence with Wi-Fi systems where the criterion used to ensure coexistence was that an LAA network does not impact existing Wi-Fi neighbors more than another Wi-Fi network.

We discussed earlier that there are two design options for LTE-based LAA LBT, that is, asynchronous and synchronous LBT. The main difference between them lies in the fact that the asynchronous LBT is based on the current DCF protocol. In this case, the LBT scheme may use IEEE 802.11 RTS/CTS signals to ensure that the channel is idle just at that moment. However, synchronous LBT is considered as a special version of asynchronous LBT, wherein, data subframes are synchronized with the licensed LTE carrier. This LBT approach required minimal changes to the LTE specifications and could use inter-cell interference coordination (ICIC) mechanism already defined in earlier releases of LTE to manage the interference among LTE base stations. The ICIC mechanism is illustrated in Fig. 8.39. In this figure, different shades represent different frequencies in the outer sectors where the same frequency is used in the inner sectors.

Deterministic channel sharing relies on LTE centralized scheduling to periodically turn off its transmission so that Wi-Fi users can access the shared channel. Among time-domain coexistence mechanisms, we have discussed CSAT and blank-subframe allocation. A blank-subframe is an LTE subframe where transmission is muted so that Wi-Fi users can access the channel. Similar to CSAT, a blank-subframe allows time-domain sharing between LTE unlicensed and Wi-Fi networks. In each radio frame, the eNB can configure a certain

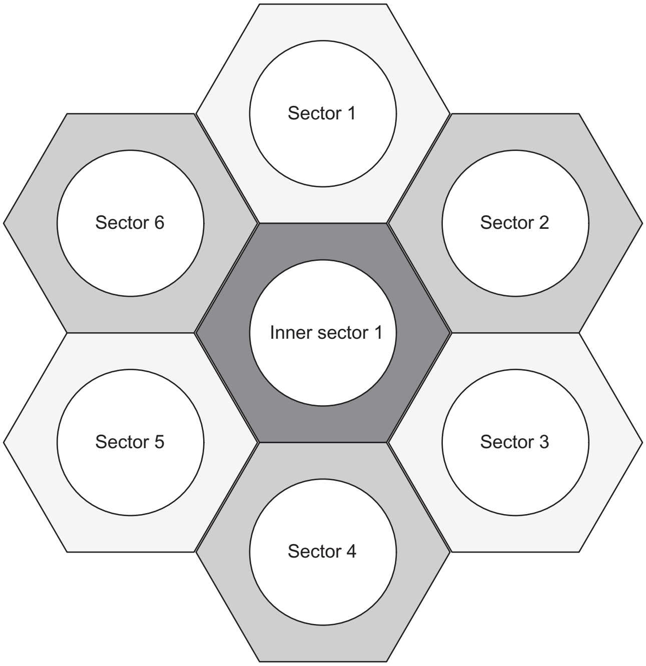

Figure 8.39
Illustration of LTE ICIC scheme where cell-center and cell-edge users have frequency reuse factor of 1 and 3, respectively.

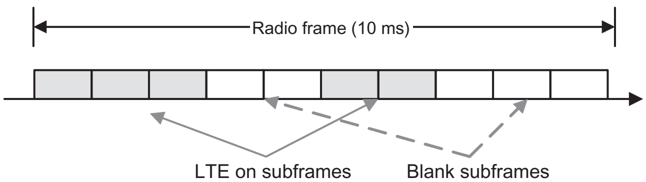

Figure 8.40
Example of blank-subframe allocation in an LTE radio frame [25].

number of blanked subframes based on the measurement of Wi-Fi's traffic load (see the example in Fig. 8.40). Fairness can be achieved by adjusting the number of blank subframes in each radio frame. Blank subframe offers more flexibility than CSAT as the ratio between the non-blank and blank subframes can be dynamically adjusted at the frame level, which is shorter than a CSAT cycle. Moreover, the positions of these blank subframes in each frame do not need to be consecutive. A blank-subframe is similar to the ABS used for enhanced ICIC (eICIC) mechanism in LTE-based heterogeneous networks. An ABS is a subframe

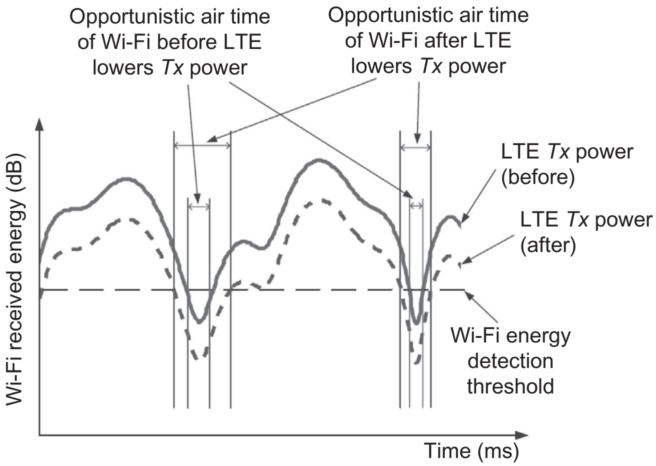

Figure 8.41
An example of Wi-Fi transmission opportunities before and after LTE power reduction [25].

during which only control and reference signals are transmitted with reduced transmit power. In contrast to ABS, a blank subframe does not include transmission of control and reference signals.

The coexistence between LTE and Wi-Fi networks by adjusting the output power of LTE nodes is an alternative method to minimize the interference. The Wi-Fi nodes typically employ energy detection to determine the activities of other users. More specifically, if the aggregate received energy is above a threshold, a Wi-Fi node would consider the channel to be busy and would postpone its transmission. For LTE/Wi-Fi coexistence, one may increase the transmission opportunity of Wi-Fi nodes by reducing the output power of the LTE nodes. As illustrated in Fig. 8.41, when the LTE transmit power is reduced, the transmission window for a Wi-Fi node becomes larger and the Wi-Fi node can more opportunistically transmit. On the other hand, the reduction in LTE transmit power will also result in lower LTE throughput due to the decrease of the SINR as a result of increased Wi-Fi transmissions.

Considering the potentially large number of deployed Wi-Fi APs and/or LTE-based LAA nodes, the backhaul and inter-node connectivity is another key challenge in such heterogeneous networks. An ideal backhaul (a dedicated point-to-point connection) is considered a link which provides (one-way) transport latency less than 2.5 ms and a throughput of up to 10 Gbps. Other types of backhaul links are considered non-ideal. The unlicensed and licensed carriers in ideal backhaul deployments can be co-located or inter-connected.

Inter-node synchronization is another deployment consideration in heterogeneous networks. Both synchronous and asynchronous scenarios have been considered between LTE-based LAA and/or Wi-Fi small cells as well as between the small cells and the macrocell(s).

Modern UEs often implement multiple RATs, where very close proximity of the RF components would cause in-device coexistence (IDC) interference. 3GPP LTE Rel-11 introduced several solutions for handling this interference and those solutions can be used to protect Wi-Fi networks during LAA operation. The basic principle is that the UE indicates IDC interference to the serving eNB which later resolves the issue by configuring the UE with an appropriate DRX cycle, performing a handover of the UE to another cell, or completely releasing one or more SCells [5]. However, it must be noted that the use of LBT in LAA would complicate the UE scheduling because there is no guarantee that a channel can be obtained for the UE at the exact time instant determined by the eNB. The LBT mechanism also limits the duration when the channel can be occupied; therefore the DRX timers should be adjusted to be long enough or the DRX cycles should be short enough to allow time for obtaining the channel access.

In LTE, when the UE detects an IDC condition, it would initially try to solve the problem internally. If this fails, the UE can inform the eNB that it is experiencing an IDC condition. Note that the detection of IDC condition in a UE is implementation specific. The UE identifies the frequencies that are suffering from IDC interference. If the UE determines that the IDC problem can be solved in a TDM-manner (i.e., by multiplexing the use of the interfering transceivers across time) the UE can indicate a TTI bitmap or DRX cycles that are affected by IDC interference to the eNB. When the eNB receives the indication, it can solve the problems by performing a handover of the UE to other frequencies, removing the problematic cell or configuring the UE with a new DRX configuration which would solve the problem. The existing IDC solutions can be used to support Wi-Fi background scanning during LAA operation. The existing IDC solutions can also be used to indicate interference problems for cases where the UE intends to use Wi-Fi on the same or adjacent carrier to the unlicensed carrier. If the eNB does not support IDC, the only way for the UE to enable Wi-Fi transmission would be to perform detach and attach procedures, and changing its capabilities to indicate that LAA is not supported. However, from a system operation viewpoint, having the UE perform detach and attach procedures is considered undesirable. Hence, eNB should enable IDC indications and respond to the IDC requests from the multi-radio UEs.

The QoS of some radio bearers might suffer when LAA is used due to support of LBT as there can be various interference sources in the unlicensed spectrum such as other RATs and LAA nodes of other operators. To improve the QoS, the characteristics of an LAA cell should be considered when mapping traffic from radio bearers to carrier(s). For example, it is better not to send critical control information, delay-sensitive data or guaranteed bit rate bearers through LAA cells, if the LBT operation is required.

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