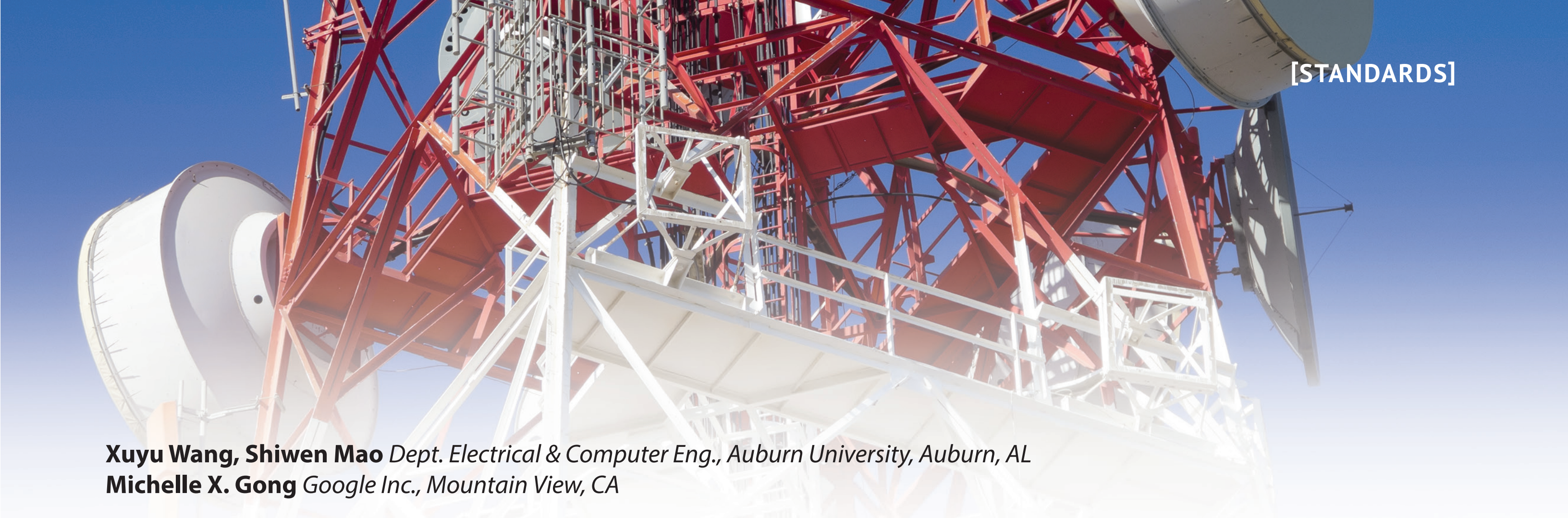

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A SURVEY OF LTE WI-FI COEXISTENCE IN UNLICENSED BANDS

With the rapid growth of mobile data, many LTE operators are interested in leveraging unlicensed bands to enhance data rates and user experience. This paper investigates the problem of the coexistence of LTE and Wi-Fi in 5 GHz unlicensed bands. We first introduce the current rules for the 5 GHz unlicensed bands and the carrier aggregation technique. We then discuss four deployment scenarios and two LTE-unlicensed (LTE-U) coexistence scenarios. Further, we provide a feature comparison between LTE and Wi-Fi in the PHY/MAC layers, and review the coexistence methods for LTE-U and Wi-Fi without or with the Listen-Before-Talk (LBT) mechanism. This paper is concluded by an examination of Wi-Fi link aggregation and in-device coexistence issues.

The rapid development of mobile devices and wireless communications, and networking techniques brings about an unprecedented growth in mobile data. The mobile industry needs to accommodate 1000 times as much data traffic, as compared to that in 2010, by 2020 [1]. To meet the 1000 times mobile data challenge, effective and innovative solutions are in need to enhance the network capacity and user experience. The Long Term Evolution (LTE) standard (Releases 10-12) leverages carrier aggregation for licensed spectrum expansion by combing multiple small bands into a larger virtual bandwidth. It is effective in exploiting the spectrum available in different bands to achieve a high network capacity [2]. However, licensed bands for LTE are limited and expensive. LTE operators are thus interested in utilizing the 5 GHz unlicensed bands. Currently, the 5 GHz unlicensed bands are mainly used by Wi-Fi, which allows better spectrum efficiency and higher data rates comparing to the 2.4 GHz unlicensed band.

There are two main methods for using LTE in the 5 GHz unlicensed bands, i.e., LTE Unlicensed (LTE-U) and Licensed-Assisted Access (LAA). LTE-U is a relatively simple mechanism in the early deployment, which does not require changes to the LTE air interface protocol [4]. Moreover, LTE-U uses LTE Release 10-12 carrier aggregation protocols, which does not require the Listen before Talk (LBT) mechanism. Thus, LTE-U is only suitable for the markets such as US, South Korea, India and China, rather than Europe and Japan with the LBT regulation. For LAA, it is approved by the 3rd Generation Partnership Project (3GPP) as Release-13, which targets a single global framework [3,5]. LAA not only meets the LBT regulation but also other regulations on, e.g., channel occupancy bandwidth and power spectral density. On the other hand, for LTE-U/LAA, it is critical to achieve a fair coexistence with other unlicensed technologies such as Wi-Fi. The goal is that LTE-U/LAA does not impact Wi-Fi services (data, voice, and video services) more than an additional Wi-Fi network deployed on

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the same carrier [3].

In this paper, we investigate the coexistence of LTE and Wi-Fi in the 5 GHz unlicensed bands. In section "LTE in 5 GHz Unlicensed Bands and Carrier Aggregation," we discuss 5GHz unlicensed spectrum and carrier aggregation, including supplemental downlink and carrier aggregation. Section "Deployment Scenarios" discusses four deployment scenarios of LTE-U. Section "Coexistence Scenarios" introduces two LTE-U coexistence scenarios, including LTE-U and Wi-Fi, and LTE-U and LTE-U, respectively. In Section "LTE vs. Wi-Fi," we provide a comparison between LTE and Wi-Fi with their PHY/MAC layer features. In Sections "Coexistence without LBT" and "Coexistence with LBT," we examine the coexistence issue without and with LBT, respectively, in detail. In Section "LTE + Wi-Fi Link Aggregation," LTE and Wi-Fi link aggregation is introduced. Finally, we conclude the paper with a discussion of in-device coexistence issue in Section "In-Device Coexistence."

	US, Europe, Japan India, China			US, Europe, Japan	US, India, China	
Current Rules	UNII-1 (100 MHz) 50mW NoDFS Indoor Only	UNII-2A (100 MHz) 250mW DFS	UNII-2B (120 MHz) No Technical Rules	UNII-2C (255 MHz) 250mW DFS	UNII-3 (100 MHz) 1W No DFS	UNII-4 (75 MHz) No Technical Rules

5.150 GHz 5.250 GHz 5.350 GHz 5.470 GHz 5.725 GHz 5.850 GHz 5.925 GHz

FIGURE 1. The 5 GHz Unlicensed Spectrum

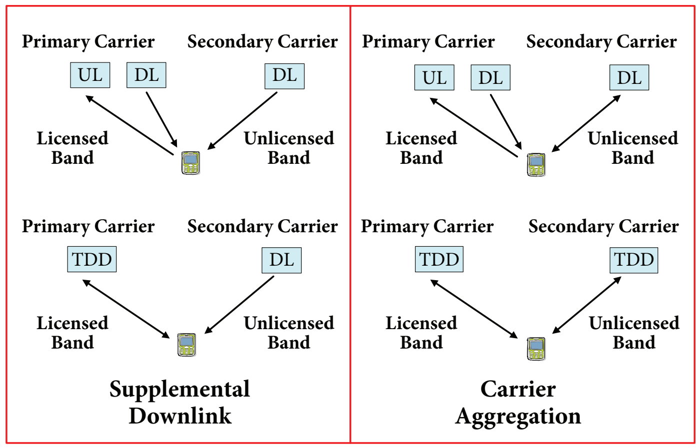

FIGURE 2. LTE-U Carrier Aggregation.

LTE IN 5 GHZ UNLICENSED BANDS AND CARRIER AGGREGATION

With increased demand for wireless access, 3GPP is becoming interested in the 5GHz National Information Infrastructure (UNII) bands from 5.150-5.925 GHz, which are mainly used by Wi-Fi networks presently. The wider spectrum in 5 GHz can be utilized by LTE operators to enhance their service in licensed bands.

As shown in Figure 1, for the 5 GHz spectrum, current rules for the different bands are not completely the same, while different countries have their regional requirements [7]. For the spectrum 5.150-5.250 GHz (UNII-1) with 100 MHz bandwidth, the stations in wireless service should be restricted to indoors and the peak conducted output power shall not exceed 50 mW. Moreover, UNII-1 does not require dynamic frequency selection (DFS) for radar avoidance. For the spectrum from 5.250-5.350 GHz (UNII-2A) with 100 MHz bandwidth, the stations in the mobile service require DFS for radar avoidance and the peak conducted output power is restricted to 250 mW. Moreover, the spectrum 5.150-5.350 GHz can be used in the US, Europe, Japan, India, and China. For the spectrum 5.470-5.725 GHz (UNII-2C) with bandwidth 255 MHz, DFS is required and the maximum peak conducted output power is 250 mW, which is available for the US, Europe, and Japan. Furthermore, the band 5.725-5.85GHz (UNII-3) with 100 MHz bandwidth does not require DFS and has the maximum peak conducted output power of 1 W, which is available in the US, India, and China. Additionally, the spectrum 5.350-5.470 GHz (UNII-2B) and 5.850-5.925 GHz (UNII-4) do not have technical rules, which will be available in the future. Thus, LTE operators can use these unlicensed bands if the above rules are satisfied.

To enhance the user experience, a unified LTE network can extend LTE carrier aggregation from licensed bands to unlicensed bands, to improve data capacity, user data rates, and coverage. Figure 2 illustrates LTE-U carrier aggregation based on supplemental downlink and carrier aggregation. Both include one carrier as the primary carrier and the other as secondary carrier [10]. For supplemental downlink, the secondary carrier is only leveraged for downlink (DL) traffic transmission. The primary carrier can be used as licensed Frequency-Division-Duplexed (FDD) or Time-Division-Duplexed (TDD) for control data and uplink (UL) traffic in the licensed bands. For carrier aggregation, the unlicensed band can be employed for DL/UL data transmission, while the licensed band can be leveraged for the control channel data and UL traffic in FDD or TDD mode.

DEPLOYMENT SCENARIOS

In Figure 3, we present the LTE-U common deployment scenario. It shows that this deployment includes one macro cell, multiple small cells with licensed carrier, and multiple small cells with unlicensed carrier. This general deployment scenario can evolve into four different scenarios, with the presence or absence of the macro cell, the allocation of licensed carriers F1 and F2, and the unlicensed carrier F3, and ideal or non-ideal backhauls. We discuss these four scenarios in the following [3,8].

In Scenario 1, the licensed small cells (the green ones, F2) do not exist. Carrier aggregation between licensed macro cell

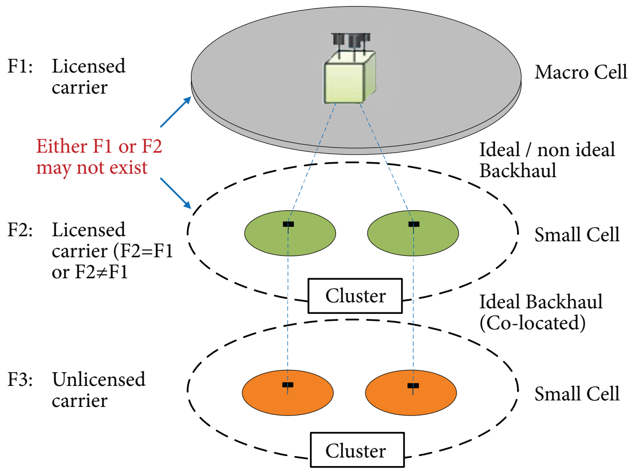

FIGURE 3. LTE-U Common Deployment Scenario.

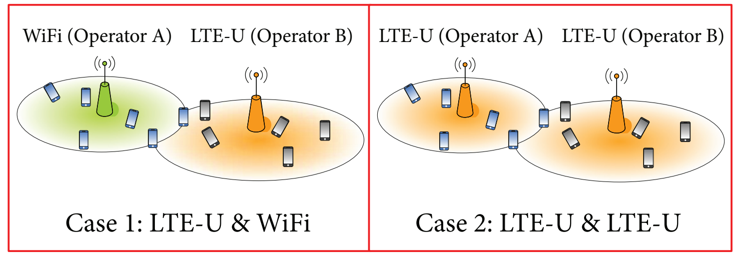

FIGURE 4. LTE-U Coexistence Scenarios.

(F1) and unlicensed small cells (F3) is implemented with an ideal backhaul (e.g., optical fiber with low latency and high throughput). Moreover, the licensed macro cell (F1) and unlicensed small cells (F3) can be non-colocated. This scenario uses one macro, thus guaranteeing the mobility management and improving coverage. This is typically used for indoor and outdoor environments.

In Scenario 2, the licensed macro cell (F1) does not exit. Carrier aggregation between licensed small cell (F2) and unlicensed small cell (F3) without macro cell coverage is implemented with an ideal backhaul and colocation. Without macro cell coverage, this scenario is proper for indoor services.

In Scenario 3, both the licensed macro cell and small cell use the same carrier (F1). Carrier aggregation between licensed small cell (F1) and unlicensed small cell (F3) is implemented with an ideal backhaul and co-location. Moreover, licensed macro cell (F1) and licensed small cell (F1) can be connected with an ideal backhaul or a non-ideal backhaul. This scenario can be used for both indoor and outdoor environments.

In Scenario 4, the licensed macro cell and licensed small cell use different carriers (F1) and (F2), respectively. Carrier aggregation between licensed small cell (F2) and unlicensed small cell (F3) is implemented with an ideal backhaul and co-location. Moreover, the licensed macro cell (F1) and licensed small cell (F2) can be connected with an ideal backhaul or a non-ideal backhaul. This scenario can also be used for both indoor and outdoor environments.

If an ideal backhaul is used between the macro cell and small cells, carrier aggregation can be implemented between a macro cell (F1), licensed small cell (F2), and unlicensed small cell (F3). If a non-ideal backhaul is employed between a macro cell and a small cell cluster, as in Scenarios 3 and 4, the small cell with an unlicensed carrier should be aggregated with the small cell on a licensed carrier in the small cell cluster by using the ideal backhaul. In addition, if dual connectivity is available, dual connectivity is used between the macro cell and small cell [3].

COEXISTENCE SCENARIOS

In this section, two LTE-U coexistence scenarios are discussed. As illustrated in Figure 4, the first case is the coexistence between Wi-Fi and LTE-U, and the second case is the coexistence between LTE-Us of different operators [9].

Case 1: LTE-U vs. Wi-Fi

LTE-U and Wi-Fi use different MAC/PHY designs and are usually operated by different operators. No matter in LBT-regulated or LBT-non-regulated markets, a proper access mechanism such as LBT for LTE-U should be introduced to avoid mutual interference if both systems use the same unlicensed carrier.

Moreover, a fair competition mechanism should also be implemented. Because there are great differences between these two systems, such as different radio frame structure and transmission scheduling (see Section "LTE vs. Wi-Fi"), the implementation leads to high complexity. Thus, a fair Time Division Multiplexing (TDM) scheme should be leveraged to avoid the interference between LTE-U and Wi-Fi if they use the same unlicensed spectrum.

Case 2: LTE-U vs. LTE-U

This is the case when LTE-Us from different operators coexist in the same 5 GHz unlicensed spectrum [16]. In the markets not regulated with LBT, neighboring LTE-U Evolved Node Bs (eNB) utilize the same unlicensed carrier at the same time, thus leading to great co-channel interference when different operators are not well coordinated in the same deployment area. A proper access mechanism such as LBT should be introduced to reduce the interference and improve the spectrum efficiency of LTE-U [16]. Moreover, when multiple LTE-U nodes simultaneously identify a clear unlicensed spectrum, interference also happens among the LTE-U nodes. Therefore, to solve this interference problem, a fair competition mechanism should be used. In fact, LBT mechanism is not mandated in the markets but a fair competition mechanism is required.

In LBT-regulated markets, a common proper access mechanism such as LBT is necessary, and a fair competition principle can be as an optional function to improve the performance of LTE-U, such as the online auction mechanism proposed in [16]. In this scenario, the operators use the same technology, so that neighboring LTE-U nodes can be coordinated if such interface between different operators exist, to share the unlicensed spectrum more efficiently. For example, two LTE-U systems can share the unlicensed spectrum in the TDM mode with proper coordination.

LTE VS. WI-FI

Table 1 provides a comparison between LTE and Wi-Fi in the PHY/MAC layers [10]. We discuss the main differences between LTE and Wi-Fi in the following.

For channel access, LTE and Wi-Fi use different channel access mechanisms, thus leading to the main difference on the coexistence of the two systems. LTE are used in licensed band, and has a centralized controller for DL/UL links, thus obtaining high spectrum efficiency and reliable transmissions. On the contrary, Wi-Fi systems do not require a centralized control, and use the Distributed Coordination Function (DCF) based on random access and contention.

For channel usage, LTE transmits for contiguous frames, and thus the channels are always on. However, Wi-Fi systems can send packets when the channel is unoccupied. Moreover, the channel is on and off based on traffic demand. Thus, when LTE and Wi-Fi systems use the same unlicensed band, the performance of Wi-Fi will be greatly impacted, while the performance of LTE systems may remain normal. The reason is that Wi-Fi systems cannot be activated due to DCF, when LTE systems are always transmitting. Thus, fairness coexistence mechanisms are needed to solve this problem.

For scheduling, LTE and Wi-Fi are both based on OFDM for both DL/UL transmissions. However, LTE systems have a smaller subcarrier space and granularity than Wi-Fi systems in the PHY layer. Moreover, LTE systems divide resources into several frames, each of which includes ten subframe 1 ms each. Resources in each subframe are allocated both along time and frequency at the granularity of Resource Blocks (RB), where the area consists of half a sub-frame with 0.5 ms and 12 sub-carriers with 180 kHz. Thus, using RB, LTE systems can share the channel among multiple users in both time and frequency domains. For Wi-Fi systems, only one user can occupy the entire channel at a time unless the Multi-User (MU) MIMO technique is employed. Thus, LTE systems have a higher spectrum efficiency than Wi-Fi systems.

For interference management, LTE systems have co-tier and cross-tier co-channel interference. The co-tier interference happens among network nodes that use the same tier in the LTE network. For example, co-tier interference happens between neighboring small cells. Cross-tier interference happens between different tiers of the LTE network. For example, the interference bewteen small cell and macro cell users in a Heterogeneous Network (HetNet). 3GPP defines enhanced Inter-Cell Interference Coordination (eICIC) methods to reduce inter-cell interference. On the other hand, Wi-Fi systems suffer from hidden and exposed terminal problems, which lead to interference or waste of efficiency. The former can be solved with Request-to-Send/Clear–to-Send (RTS/CTS) in Carrier Sense Multiple Accesses with Collision Avoidance (CSMA/CA). Another difference is that Cell-specific Reference Signal (CRS) interference exits in LTE but no such interference to Wi-Fi when there is no data transmission.

For retransmission, LTE systems leverage Hybrid Automatic Repeat Request (HARQ), and thus failed transmissions can be reused by combing with retransmitted data. LTE with HARQ achieves a higher efficiency than single-loop Automatic Repeat Request (ARQ) with acknowledgement (ACK) in Wi-Fi systems.

Such big difference features between LTE and Wi-Fi pose great challenges in the design of an effective coexistence mechanism. These factors should be carefully considered to design a fair and efficient coexistence mechanism for LTE and Wi-Fi networks in the unlicensed band.

TABLE 1. Comparison of LTE and Wi-Fi

Channel access	Centralized controller on DL/UL. LTE does not contend	Contention based Distributed Coordination Function (DCF)
Channel usage	Continuous frames, always on	On-demand, on and off
Scheduling	The channel is shared by multiple users at time and frequency domains	One user uses the entire channel at a time
Interference	Co-tier/cross-tier co-channel interference	Hidden/exposed terminal, collision
Retransmission mechanism	HARQ combining is used in retransmission	No HARQ combining; Single-loop ARQ with ACK can be used

COEXISTENCE WITHOUT LBT

In some countries that don't require LBT, such as the United States, South Korea, and China, coexistence mechanisms between LTE-U and Wi-Fi should be carefully designed. The advantage is there is no modification to the release 10/11 PHY/MAC standards. Moreover, it is guaranteed that the resource sharing should be fairly implemented between LTE-U and Wi-Fi.

One technique proposed by Qualcomm [4] includes three components, as shown in Figure 5. After initialization and configuration, LTE-U performs channel selection, to scan the channels in unlicensed bands. If a clear channel is identified, LTE-U will occupy the channel with a full duty circle for Secondary DL (SDL) transmission. If there is no clear channel, Carrier-Sensing Adaptive Transmission (CSAT) is used to share the channel with Wi-Fi [11]. In addition, SDL carrier can be opportunistically accessed in terms of load demand. If there is low load, SDL carrier should be turned off, thus reducing the interference to neighboring Wi-Fi access points (AP). If the load is high, channel selection should be performed again. We discuss these three main mechanisms in the following.

Channel Selection

LTE-U implements a scanning procedure to search for clear channels for SDL carrier transmission, which is based on LTE and Wi-Fi measurements performed in the initialization phase and periodically during the SDL operation stages. Scanning can be passive or active, carried out every few seconds, and channel selection can be made at any time, during 10s of seconds.

If several clear channels in unlicensed bands are identified, LTE-U generally chooses the clearness channel, thus potentially avoiding primary channels of Wi-Fi and the channels of other LTE-U operators. If LTE-U detects interference in the operating channel and identifies some other available channels in unlicensed bands, it will switch to another clear channel that has less interference based on LTE Release 10/11 procedures.

The interference level can be measured by energy detection, where the number of interference sources and types are unknown. Thus, LTE and Wi-Fi measurements are employed to enhance interference detection. For example, LTE network listening is used to find the LTE-U primary Synchronization Signal (PSS), Secondary Synchronization Signal (SSS), and Physical Broadcast Channel (PBCH) channels. Wi-Fi preambles are detected to estimate the number of neighboring Wi-Fi APs in a given channel. Moreover, user measurements are utilized to detect hidden nodes and choose a clear channel. In general, channel selection can satisfy the LTE-U and Wi-Fi coexistence requirements if the load is low.

CSAT

When the scanning procedure cannot identify a clear channel in unlicensed band, LTE-U needs to share the channel with neighboring Wi-Fi access APs or other LTE-U systems by executing the CSAT algorithm. In addition, no clear channels can be found in the dense deployment of LTE-Us and Wi-Fi APs.

In general, the coexistence methods in unlicensed band are by using LBT or CSMA for Wi-Fi, which uses contention based access. For CSMA or LBT, the medium should be sensed, and accessed if it is sensed clear. The key idea of these techniques is to implement TDM for coexistence.

In fact, CSAT also leverages TDM coexistence for medium sensing. However, it senses the medium about 10s of msec to 200 msec, which is longer than LBT or CSMA techniques. Moreover, based on the measured medium activities, CSAT can turn off LTE transmission proportionally. In particular, CSAT uses a duty cycle, so that LTE-U can adjust the on/off ratio and transmission power. The duty cycle can be a few hundreds of msec. The activation/de-activation procedures can be adaptively adjusted for controlling the transmission delay. During the CSAT on period, LTE-U can transmit in high power. During the CSAT off period, LTE-U can operate in low power or even turn off to avoid interference to neighboring Wi-Fi users. Moreover, Wi-Fi can resume normal transmission during the CSAT off periods. To implement CSAT algorithm in LTE, the Almost Blank Subframe (ABS) feature can be used [6].

In summary, CSAT can ensure compatibility with Rel. 10/11 UE PHY/MAC standards. Also, CSAT can achieve fair and efficient channel sharing between LTE-U and Wi-Fi.

Opportunistic SDL

SDL carrier can be utilized in an opportunistic manner in the unlicensed band. In general, the opportunistic SDL transmission is made based on the load demand. If the downlink load of the small cell is high and there are active users using the unlicensed band, SDL transmissions should be turned on for strengthening data offloading in the unlicensed band. If the downlink load of small cell is low, or there are no active users using the unlicensed band, the SDL transmission should be turned off to reduce the interference to neighboring Wi-Fi APs and other LTE-U operators.

COEXISTENCE WITH LBT

To provide a fair channel sharing and accessing mechanism, many markets such as European, Japan and India mandate the use of LBT in the unlicensed 5150-5350 MHz and 5470-5725 MHz bands. With LBT, each equipment performs Clear Channel Assessment (CCA) based on energy detection, which can determine the presence or absence of other occupants in the channel. The equipment cannot access the channel when the energy level is above the CCA threshold. Besides the regulatory requirements, LBT is the technique for fair sharing of the unlicensed spectrum. It is considered an important feature of LTE-LAA for a single global solution framework.

Based on European Telecommunications Standards Institute (ETSI) regulatory rules, two LBT mechanisms are mainly used in LTE-LAA. One mechanism is Frame based Equipment (FBE) and the other is Load based Equipment (LBE) [3,12], as shown in Figure 6. In the following, we discuss these two mechanisms in detail, and compare their advantages and drawbacks.

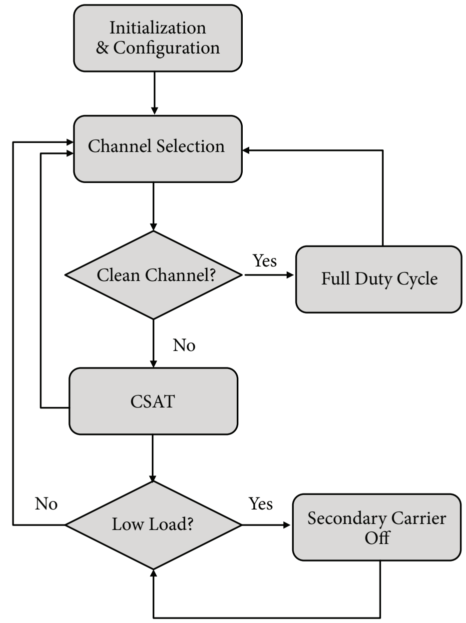

FIGURE 5. Coexistence Flow Chart for LTE-U. [4]

FBE-Based LBT Mechanism

In FBE, the equipment is not directly demand-driven but has a fixed frame period, where CCA is implemented. In Figure 6, the channel occupancy time is between 1 ms to 10 ms, and the minimum idle period is at least 5% of the channel occupancy time utilized by the equipment in a fixed frame period. Moreover, the CCA period is at least 20 us. If the operating channel is sensed clear, the equipment can transmit immediately for a duration equal to channel occupancy time. If the operating channel is occupied, the equipment cannot transmit on the channel during the next fixed frame period.

FBE-based LBT is rather simple for the design of reservation signal or channel. It also requires less standardization effort than LBE-based LBT. For FBE-based LBT, it is easy to obtain reuse factor 1 for an operator by aligning the transmission period and the CCA period among synchronized nodes of the operator. Moreover, the measurement and coordination can be easily implemented for a fixed frame structure. However, compared with CSMA based Wi-Fi, the chance may be low for FBE-based LBT to access the unlicensed channel when co-existing with some LBE, because the CCA can be executed once every fixed frame period. In addition, FBE-based LBT leads to a lower efficiency of resource usage and larger delay, because arriving traffic is often blocked when the channel is busy.

LBE-Based LBT Mechanism

In LBE, the equipment is required to determine whether the channel is idle or not. If the equipment finds a clear operating channel, it will immediately transmit. Otherwise, an Extended CCA (ECCA) is performed, where the channel is observed for the duration of a random factor *N* multiplied by the CAA time. *N* is defined as the number of clear slots so that a total idle period should be observed before transmission. Its value should be randomly chosen in the range from 1 to q, whose value is from 4 to 32, The *N* value is set to a counter. When a CCA slot is idle, the counter will be decreased by one. The equipment can transmit if the counter reaches zero. In addition, the maximum channel occupancy time is given by (13/32)*q ms. Thus the maximum channel occupancy time is 13 ms when *q* equals to 32. In Fig. 6, we can see that $N = 4$, and there are two failed CCA slots and four successful CCA slots. After the counter reaches zero, the data transmission is performed.

The equipment using LBE-based LBT mechanism can access the channel immediately after the channel becomes idle, while the equipment using FBE-based LBT mechanism needs to wait till the next CCA time and may lose the channel access. In addition, LBE-based LBT has a higher efficiency of resource usage and lower delay than FBE-based LBT. Further, it can achieve fair access opportunity between LTE-U and Wi-Fi, because Wi-Fi uses the same access method. On the other hand, LBE-based LBT requires more specification and changes than FBE-based LBT. Moreover, though the nodes of one operator are nearly synchronized, it is still difficult to obtain the reuse factor 1 operation, because transmission time and CCA time are often unaligned due to different interference conditions. When synchronization with LTE-U is required, reservation signals are needed. Also, cross-link interference cannot be avoided.

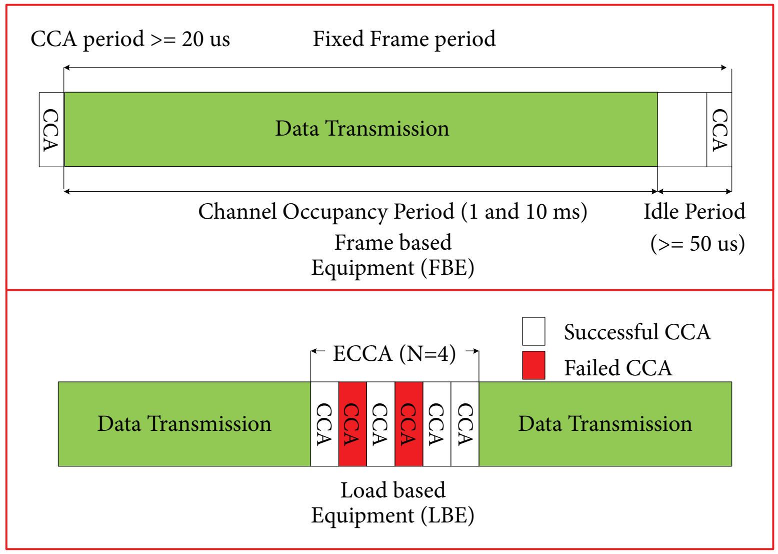

FIGURE 6. Frame-Based Equipment (FBE) and Load-Based Equipment (LBE).

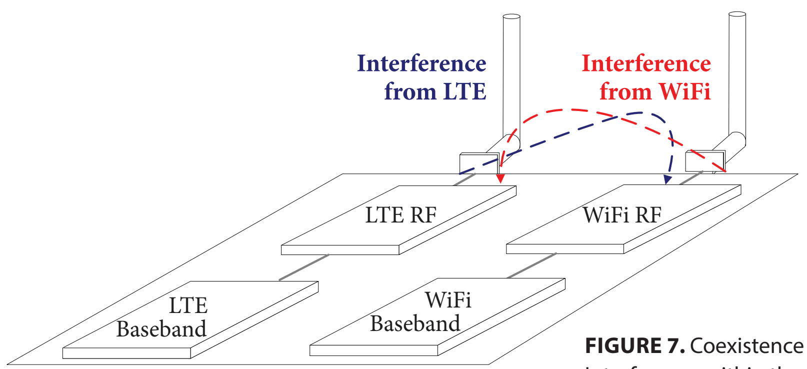

FIGURE 7. Coexistence Interference within the Same UE

LTE + WI-FI LINK AGGREGATION

LTE and Wi-Fi link aggregation (LWA) is an alternative to deploying LTE in unlicensed band, which has a good potential for wireless and mobile industry development [13] [14].

LWA leverages unlicensed band in 5 GHz like LTE-U and LTE-LAA for transmission. The difference is, in LWA, the LTE data payload can be transmitted by both LTE and Wi-Fi. It means that some data is sent by LTE in the licensed bands and the rest is tunneled by Wi-Fi in unlicensed bands; the data payload is allocated at the LTE eNB and aggregated at the user device. Moreover, Wi-Fi APs should be connected to LWA base stations and can leverage LTE core network functions. While LTE-U/LAA requires new device and network hardware, LWA only needs to update software for devices and networks with a relatively lower cost. Moreover, LWA does not cause the fair access problem because it only uses Wi-Fi transmissions in unlicensed bands.

The LWA framework includes LWA user (UE), LWA-aware Wi-Fi AP, and LWA eNB. Moreover, LWA eNB and Wi-Fi AP can be co-located or non-co-located. In LWA, first, LWA eNB sends Packet Data Convergence Protocol (PDCP) packets on PDCP layer, where some are scheduled by LTE and the rest by Wi-Fi APs after encapsulating them in Wi-Fi frames. Once the UE receives all the packets from LTE and Wi-Fi, PDCP re-ordering and PDCP aggregation are performed to recover the DL data. Moreover, Wi-Fi APs connected with LWA eNBS can report channel state information (CSI) to LWA eNB. It can be used to consider whether there are Wi-Fi APs for LWA use. By managing resource based on traffic and

CSI conditions between LTE and Wi-Fi, LWA eNB can effectively enhance the total system performance with effective traffic scheduling.

IN-DEVICE COEXISTENCE

Interference In-Device Coexistence (IDC) is recognized as the main problem for obtaining high wireless capacity [3]. For example, Figure 7 shows the coexistence interference within the same UE. We can see that the interference from LTE affects the Wi-Fi RF transceiver, while the interference from Wi-Fi also affects the LTE RF transceiver. Fortunately, 3GPP Release 11 provides solutions to deal with IDC interference on adjacent frequencies or sub-harmonic frequencies for multiple radio transceivers.

The LTE-U design should support other types of radio modems, which are used to detect Wi-Fi network during LTE-U transmission. Note that it does not mean LTE-U and Wi-Fi having concurrent transmissions. The solution to avoid IDC interference in Release 11 is discussed in the following.

First, the UE detects and tries to deal with the interference on its own by TDM model (multiplexing the use of the interference transceivers in time). If the interference cannot be solved, the UE requires assistance from the LTE eNB by sending an indication as a bit-map or Discontinuous Reception (DRX) cycles. If the LTE eNB obtains the indication, the interference problem can be solved by getting rid of the problematic cell or configuring the UE by a DRX-configuration, or by implementing a handover of the UE to other carriers.

Moreover, the solution to IDC interference can be used for supporting Wi-Fi background scanning during LTE-U operation. The existing IDC solution can also be leveraged to indicate the interference problems that UE utilizes Wi-Fi on the same or adjacent frequency to the unlicensed band. When LTE eNB cannot enable IDC, it should use the detach and attach procedures for the UE to enable Wi-Fi transmission, and indicate that LT-U should not be supported.

On the other hand, when LTE-U and Wi-Fi are for concurrent DL transmissions at the same unlicensed band, IDC interference becomes serious. Fortunately, the mobile devices are equipped with both LTE and Wi-Fi antennas, which can theoretically decode LTE and Wi-Fi transmissions [15]. The solution is to perform LTE and Wi-Fi channel estimation without clear reference symbol and to decode two interfering cross-technology OFDM signals.

CONCLUSIONS

This paper presented a survey of LTE and Wi-Fi coexistence in 5 GHz unlicensed bands. We provided detailed discussions on the rules for the 5 GHz unlicensed bands, carrier aggregation, deployment scenarios, and LTE-U coexistence scenarios. We then focused on the existing coexistence mechanisms. We concluded this article with an introduction to LWA and IDE. ■

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