Recent Advances of LTE/WiFi Coexistence in Unlicensed Spectrum

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Abstract

U-LTE is a new wireless technology that is currently being developed by industry and academia to offer LTE service in unlicensed spectrum. U-LTE addresses spectrum shortage from 4G LTE cellular networks by allowing them to operate in unlicensed bands. To ensure fair spectrum sharing among different wireless technologies (LTE and WiFi in particular), a number of coexistence mechanisms have been proposed. These mechanisms operate in the time, frequency, or power domains to minimize potential adverse effects from LTE. Based on these mechanisms, a number of U-LTE standards are being developed by industry. In this article, we present recent advances in this exciting area by reviewing the state-of-the-art LTE/WiFi coexistence mechanisms and show how they are incorporated into industry standards. We also point out several key challenges and open problems for future research.

Introduction

The demand for mobile data traffic has been growing exponentially over the last decade and the trend will continue in the foreseeable future [1]. While the development of 5G cellular communications is underway, current wireless traffic will continue to be supported by LTE or LTE-Advanced (LTE-A) systems. Consequently, it remains an important task to address the spectrum scarcity problem for licensed LTE. Given that unlicensed spectrum is being made available for commercial use, how to extend LTE to unlicensed spectrum has become a popular research topic in both academia and industry.

Supporting LTE over unlicensed bands is not trivial. The key challenge is how to achieve harmonious coexistence between LTE and other systems that are already operating in these bands. Conventional LTE cannot operate in unlicensed spectrum as it has no concern for cross-technology coexistence. For example, transmissions in an LTE radio access network (RAN) are continuous in time, and subject to centralized scheduling at the eNodeB (eNB). Even in the absence of data traffic, control and reference signals are transmitted over the air (at the OFDM symbol level) and are ubiquitous over time and its channel bandwidth. In contrast, WiFi was designed for opportunistic access among its users and is ideally suited for the unlicensed spectrum. Its distributed coordination function (DCF) uses contention-based CSMA/CA protocol for channel access. A WiFi node can only transmit when there is no other user occupying the channel. This fundamental difference between centralized LTE operation and distributed WiFi access could result in significant performance degradation of WiFi networks if LTE operates directly in the same band [2]. Simply put, LTE can easily shut out WiFi entirely and monopolize the use of unlicensed spectrum. This phenomenon has raised serious concern for the WiFi community. To address this issue, a number of mechanisms have been proposed to modify LTE to make it more amenable to coexistence with other wireless technologies (so-called unlicensed LTE (U-LTE)). These modifications span the time, frequency or power domains.

Within industry standardization bodies, a number of U-LTE standards have been developed in recent years. These include LTE-U, licensed assisted access (LAA), enhanced LAA (eLAA) and MulteFire. LTE-U was first introduced by Qualcomm [3], and later standardized by the LTE-U Forum [4]. LTE-U operates with the so called supplemental downlink (SDL) mode, which uses the unlicensed spectrum only for downlink data transmission. LAA, which was standardized in 3GPP Release 13, is similar to LTE-U except that it employs listen-before-talk (LBT) as the primary coexistence mechanism [5]. eLAA is an evolution of LAA under development in 3GPP Release 14. It can support both downlink (DL) and uplink (UL) transmissions in unlicensed spectrum [6]. In contrast to the above standards, MulteFire is designed to operate solely in the unlicensed bands without the use of an anchor licensed band [7, 8]. It is being discussed in the newly formed standardization body "MulteFire Alliance." Its WiFi-like deployment and LTE-like performance make it very attractive to operators who may no longer need to own or rely on any licensed spectrum. We also note that there is an approach called LTE-WLAN aggregation (LWA) [9], that has been standardized in 3GPP Release 13. In LWA, transmissions in licensed and unlicensed spectrums are supported separately by LTE and WiFi interfaces, respectively. LWA is implemented at the transport layer, where user data is separated into two traffic streams. Traffic sent by LTE interface uses licensed spectrum, while traffic sent by WiFi interface uses unlicensed spectrum. That is, under LWA, the LTE interface does not access unlicensed spectrum.

In this article, we focus on recent advances in the development of U-LTE. In the following sections, we discuss government regulations on unlicensed bands that are made available to U-LTE. Following that we discuss different mechanisms proposed for U-LTE to coexist with other wireless technologies. Then we review recent standardization efforts on U-LTE in industry. Finally, we discuss a few technical challenges and open problems. The final section concludes this article.

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Unlicensed Bands Open to LTE

Unlicensed (or licensed-exempt) frequency spectrum is marked by regional regulatory authorities for unlicensed wireless technologies. For example, the Federal Communications Commission (FCC) in the U.S. has released several bands in the 2.4 GHz (industrial, scientific, and medical (ISM)), 5 GHz (unlicensed national information infrastructure (U-NII)) and 60 GHz millimeter-wave (mmWave) spectrums for unlicensed commercial use. Currently, wireless technologies operating in these bands include ZigBee, Bluetooth, and WiFi. Commercial cellular operators now have a strong motivation to offer LTE service in unlicensed spectrum due to the pressure of traffic growth in their licensed spectrum.

Currently, the 2.4 GHz spectrum is already heavily utilized by ZigBee, Bluetooth, and WiFi. In contrast, bands in 5 GHz are used by 802.11a and 802.11n with limited utilization. Compared with 2.4 GHz spectrum, the 5 GHz spectrum has wider bandwidth but shorter communication range (due to higher path loss). For small cell deployment, this does not pose a serious issue as the effective coverage for a small cell is typically no more than several tens of meters. U-LTE is likely to be deployed only in small cells, due to regulatory restrictions on transmit power in unlicensed spectrum. It is possible that U-LTE systems deployed in the U.S. may be able to utilize all of these bands in 5 GHz. The large amount of available bandwidth in the 5 GHz spectrum offers considerable design space and flexility for U-LTE.

In the U.S., the use of 5 GHz unlicensed spectrum is subject to FCC part 15 regulations [10]. An illustration of unlicensed 5.15–5.925 GHz spectrum in the U.S. is shown in Fig. 1. Currently, unlicensed wireless systems are allowed to 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 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 dynamic frequency selection (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 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. DFS is used for unlicensed devices to detect radar signals and change their operating channels whenever the radar systems become active. DFS should be adopted in the UNII-2A and UNII-2C bands to protect radar signals.

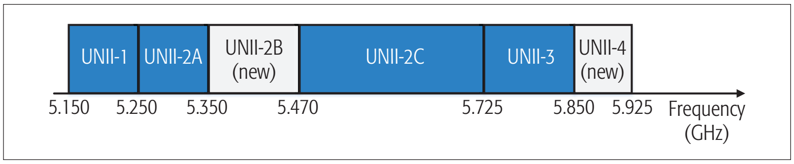

FIGURE 1. Bands in the 5 GHz unlicensed spectrum in the U.S.

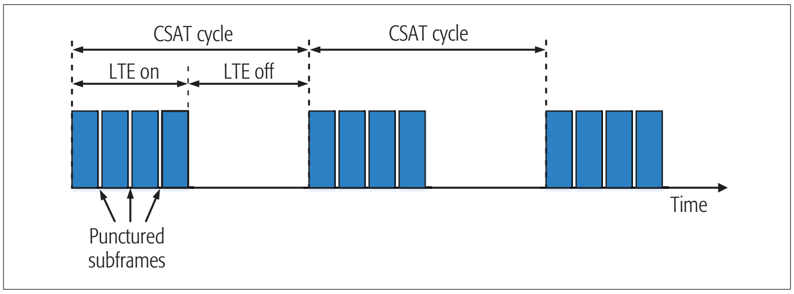

FIGURE 2. Gating cycles in CSAT and punctured subframes.

Coexistence Mechanisms

Coexistence mechanisms for U-LTE can be classified based on the frequency, time, and power domains. In the frequency and time domains, the goal is to separate transmissions of LTE and WiFi (in frequency and time, respectively), while in the power domain, the goal is to adjust the output power of LTE nodes for a desired trade-off between LTE throughput and opportunistic WiFi transmission. In the rest of this section, we discuss some key mechanisms in each domain.

Frequency Domain

Referring to Fig. 1, there are a few blocks of bandwidth in the 5 GHz regime, and each block can be further sliced into more channels. Under current carrier aggregation techniques, LTE can aggregate multiple (no more than five) channels in unlicensed bands. Since a WiFi access point (AP) operates only on one channel, it is likely that there exist some clean channels available to U-LTE systems. If U-LTE can identify these clean channels, then it can choose them for transmission. In the case that a clean channel is not available, LTE will measure the interference level on each channel, and identify the channel(s) with the lowest interference for unlicensed data transmission [3]. Interference can be measured by energy detection, technology-specific interference detection, and user-assisted technologies. The aggregate received interference power on a channel is first detected without considering types and the number of interfering sources. Then technology-specific detection is employed to determine WiFi preambles or other U-LTE systems' control and reference signals. Useful information such as the number of WiFi APs and stations (a measure of potential traffic load in WiFi networks) can be estimated from the received WiFi preambles. In addition, user-assisted measurements could be used to sense hidden nodes on a channel.

Time Domain

Deterministic Sharing: The basic idea of deterministic sharing is to rely on LTE's centralized scheduling to periodically turn off its transmission so that WiFi users can have adequate access time. In this article, we discuss two representative mechanisms: carrier-sensing adaptive transmission (CSAT) [11], and blank-subframe allocation [12, 13].

CSAT: Under CSAT, time is broken up into TDM cycles, with each cycle consisting of U-LTE "on" and "off" periods, as shown in Fig. 2. Denote T_{CSAT}, T_{ON} and T_{OFF} as the durations of a gating cycle, the "on" period, and the "off" period,

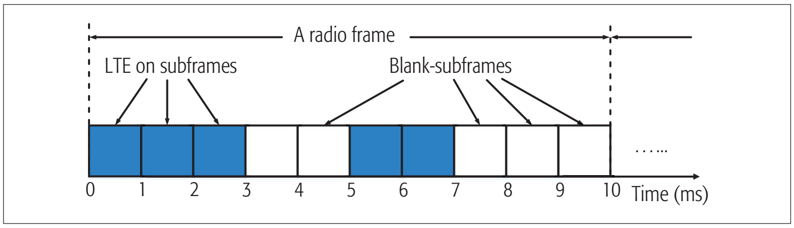

FIGURE 3. An example of blank-subframe allocation in a radio frame.

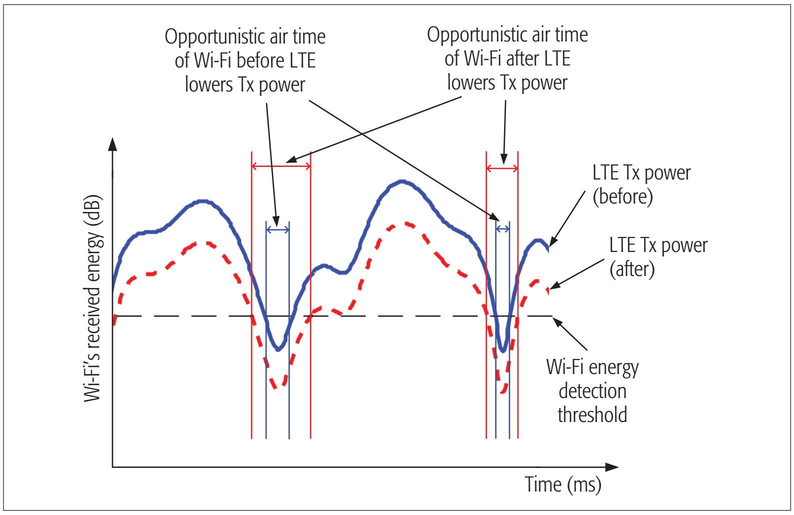

FIGURE 4. An illustration of WiFi's opportunistic air time before and after LTE lowers its transmit power level.

respectively. The ratio T_{ON}/T_{OFF} should be dynamically adjusted based on measurement of WiFi's utilization during each "off" period. Through such adaptation of "on" and "off" periods, a fair sharing of air time between LTE and WiFi may be achieved. Measurement time for WiFi's utilization should be set sufficiently long (e.g., from $\sim 10^1$ ms to 200 ms) to ensure reasonable accuracy [3]. Such measurement is mainly done through detection of WiFi preambles.

To better support delay-sensitive data and control packets in WiFi, subframe[1] puncturing can be employed during U-LTE "on" periods. Referring to Fig. 2, small but frequent gaps are introduced ("punctured") during "on" periods so that some subframes are completely muted and not used for transmission. During these punctured subframes, WiFi nodes can access the channel to transmit delay-sensitive or critical control packets. As a result, WiFi's delay performance and reliability may be improved. In general, only one punctured subframe for every 10s of milliseconds is needed.

Alternatively, setting a shorter CSAT cycle may be an effective way to improve WiFi's delay performance. However, since transmission collision between LTE and WiFi might occur at the beginning of each "on" period, an overly short CSAT cycle and thus frequent U-LTE "off/on" switching may result in more collisions and decrease spectral efficiency. At present, T_{ON} may be set as short as 20 ms [11].

Blank-Subframe: A blank-subframe is a subframe on a channel during which a U-LTE node is completely muted so that WiFi users can access the channel [13]. Similar to CSAT, a blank-subframe allows TDM-like air time sharing between U-LTE and WiFi. In each radio frame (defined as ten consecutive subframes), the U-LTE eNB can set a certain number of subframes blank based on measurement of WiFi's traffic load. Fairness could 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 frame-level, which is shorter than a CSAT cycle. Also, the positions of these blank-subframes in each frame do not need to be consecutive. An example of a blank-subframe allocation for a radio frame is given in Fig. 3.

A blank-subframe is similar to the almost-blank-subframe (ABS) used for enhanced inter-cell interference coordination (eICIC)) in LTE-A heterogenous networks. An ABS is a subframe 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 and thus is an absolutely silent subframe.

Random Sharing: Random sharing is a contention-based medium access technique similar to CSMA/CA used by WiFi. It is also known as *listen-before-talk* (LBT) in the LTE community. Before transmission, an LTE node remains muted and performs carrier sensing until conditions for transmission are met. A major strength of LBT is that it meets regulatory requirements in all regions of the world. It is accepted by both the LTE and WiFi communities due to its similarity to CSMA/CA. Two versions of LBT are available, namely, *frame-based* LBT and *load-based* LBT.

Frame-based LBT is based on a fixed frame structure. Similar to CSAT, it decomposes the air time of a channel into continuous frames with fixed duration. Each frame is further divided into an idle period and a channel occupancy period. The LTE node must remain muted during an idle period. At the end of an idle period, a carrier sensing interval, called *clear channel assessment* (CCA), is performed to check channel status. CCA is typically of tens of μs. If the channel is sensed idle, then the LTE node can transmit in the following channel occupancy period; otherwise, it cannot transmit. The channel occupancy period is of 1 to 10 ms, and an LTE node is only allowed to transmit during this period. Frame-based LBT is defined as frame-based equipment in [14].

Load-based LBT does not have any fixed frame structure. When an LTE node is awakened from idle and attempts to transmit a data burst, an initial CCA is triggered. If the channel is sensed idle during CCA, the node starts to transmit immediately; otherwise, it proceeds to perform an extended CCA (eCCA). During an eCCA, the node follows the following process:

1) It first generates a counter N (randomly) no larger than a contention window.
2) Once the carrier becomes idle, the node waits until the carrier remains idle for an additional eCCA defer period (e.g., 34 μs).
3) After the eCCA defer period, counter N is decremented by one each time the channel stays idle for an eCCA slot (e.g., 9 μs).
4) Any time the node senses the channel busy, the process goes back to step 2.

[1] An LTE subframe has a duration of 1 ms.

Mechanism	Domain	Key features	Operational time scale	Strengths	Limitations
DCS	Frequency	Based on energy detection, technology-specific detection and user-assisted measurement.	$\sim 10^2$ ms to $\sim 10^1$ s	Zero interference to Wi-Fi when clear channels are available; low complexity.	Contingent upon availability of clear channels.
CSAT	Time	TDM based; centralized scheduling by LTE; based on carrier sensing.	$\sim 10^1$ ms to $\sim 10^2$ ms	Retain LTE's centralized scheduling; no impact on LTE air interface protocol.	Cannot meet certain regional regulations; channel access dictated by LTE; potentially high probability of packet collision at the beginning of LTE "on" period.
BS	Time	TDM based; similar to ABS; centralized scheduling by LTE; based on carrier sensing.	$\sim 10^1$ ms to $\sim 10^2$ ms	Retain LTE's centralized scheduling; no impact on LTE air interface protocol; more flexible than CSAT.	Cannot meet certain regional regulations; channel access dictated by LTE; potentially higher probability of packet collision than CSAT.
Frame-based LBT	Time	Contention based; fixed frame structure; adaptation based on carrier sensing.	$\sim 10^0$ ms to $\sim 10^1$ ms	Meet global regulations; retain LTE's centralized scheduling; fewer packet collision; more friendly to Wi-Fi than CSAT.	Potentially lower spectral efficiency (than deterministic channel access and load-based LBT); need to modify LTE air interface protocol.
Load-based LBT	Time	Contention based; similar to CSMA/CA; adaptation based on carrier sensing.	$\sim 10^0$ ms to $\sim 10^1$ ms	Meet global regulations; fewer packet collision; more friendly to Wi-Fi than CSAT.	Potentially lower spectral efficiency (than deterministic channel access); need to modify LTE air interface protocol.
TPC	Power	Centralized scheduling by LTE; based on interference measurement.	$\sim 10^1$ ms to $\sim 10^2$ ms	Meet global regulations; no impact on LTE air interface protocol.	Typically used together with other coexistence mechanisms.

TABLE 1. A summary of coexistence mechanisms.

5) When counter N reaches zero, the node starts to transmit. To avoid channel capture (one node monopolizes channel usage), an LTE node must perform an eCCA process between consecutive transmissions. Load-based LBT is employed in the design of a channel access procedure in the 3GPP standard [6].

Power Domain

Transmit power control (TPC) aims to improve coexistence between LTE and WiFi networks by adjusting the output power of LTE nodes. WiFi nodes typically employ energy detection to determine activities of other users. Specifically, if the aggregate received energy is beyond a threshold, a WiFi node would consider the channel busy and postpone its transmission. For LTE/WiFi coexistence, we may increase the transmission opportunity of WiFi nodes by reducing the output power of LTE nodes. The idea of TPC is illustrated in Fig. 4. When we lower LTE transmit power, the transmission window for a WiFi node becomes larger and the WiFi node can do more opportunistic transmissions. On the other hand, the reduction of LTE transmit power will also result in lower LTE throughput, as its signal-to-interference-and-noise ratio (SINR) decreases due to increased WiFi transmissions.

There are existing works in the literature that have considered TPC for LTE/WiFi coexistence [15, 16]. In [15], Sagari *et al.* considered joint optimization of TPC and TDM channel access in multiple WiFi and U-LTE networks. In [16], Chaves *et al.* investigated uplink TPC of U-LTE to achieve a balance of performance between LTE and WiFi networks.

To conclude this section, we present a summary of the coexistence mechanisms that we have discussed in this section in Table 1.

Standardization Efforts

In this section, we discuss industry standardization efforts for U-LTE. Our discussion will focus on major standards such as LTE-U, LAA, eLAA and MulteFire. Recall that LWA does not involve an LTE interface operating in unlicensed bands and therefore does not have coexistence issue. Hence, its discussion is beyond the scope of this article.

LTE-U

LTE-U is the first proposed LTE standard for operating in unlicensed spectrum [3]. It is fully compatible with 3GPP Release 10/11 and does not require any change of LTE specifications. It leverages the carrier aggregation technology introduced in 3GPP Release 10 and allows DL transmission in unlicensed UNII bands (i.e., SDL mode). Since anchor carrier is in licensed spectrum, service reliability can be guaranteed.

The coexistence mechanisms used in LTE-U are DCS and CSAT, which are defined by the LTE-U Forum. First, DCS ensures that the LTE-U network identifies and selects a subset of cleanest channels for communication. When LTE-U has to share the same channel with other users, CSAT would be used to set the "on" and "off" periods in a gating cycle. The duration of the "on" period is adjusted based on results from channel sensing. The detailed procedure of the algorithm is as follows. SDL transmission is triggered opportunistically, depending on whether the traffic load in the network is high or not. If the licensed spectrum has enough resources to meet the LTE-U network's traffic demand, then the unlicensed bands will not be used. During SDL transmission, the DCS module monitors the interference energy level on the operating channel, and will switch channel if the detected interference energy is above

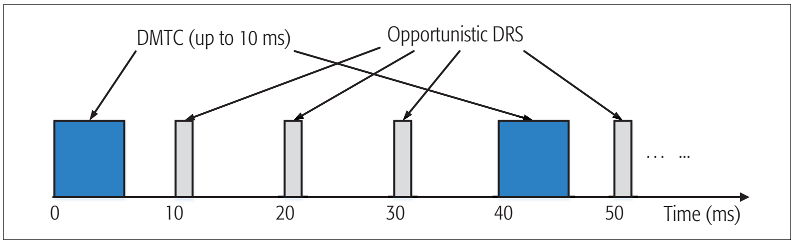

FIGURE 5. Serving cell DMTC and opportunistic DRS transmission.

a predefined threshold. In the case that no clean channel is available, CSAT will be used. When all backlogged data is cleared, the SDL transmission is de-activated.

Licensed Assisted Access

LAA is a standard formalized by 3GPP in Release 13. Different from LTE-U, LAA employs LBT as the carrier sharing strategy to meet the regulations in different regions of the world (e.g., Europe and Japan) [5]. While LTE-U is designed for early deployment of 3GPP Release 10/11 based U-LTE in regions without LBT requirement, LAA's goal is to provide a single-solution framework that can meet any regional regulatory requirement. Key LAA functions include the following [5].

Listen-Before-Talk: The goal is to preserve opportunistic medium access and prevent any player from monopolizing the spectrum.

Maximum Duration for Transmission: In regions such as Europe and Japan, continuous transmission in unlicensed spectrum is prohibited. The maximum duration of every transmission burst is upper bounded by a predefined limit.

Downlink-Only Transmission: LAA supports LBT-based DL-only transmission in unlicensed spectrum.

Dynamic Channel Selection: LAA continuously measures the interference status across available bands in the 5 GHz spectrum and switches to the least-loaded channel(s).

Dynamic Frequency Selection: In certain bands in the 5 GHz spectrum, regulation requires that all secondary unlicensed users must be able to detect the presence of radar signals and switch operating frequencies once radar signals are present. This requirement is termed dynamic frequency selection (DFS).

Transmit Power Control: TPC is mandated on certain frequency bands (e.g., UNII-2A and UNII-2C bands in the US) to keep the transmit power down within the regulation limit.

Other functionalities such as synchronization, channel state information (CSI) reporting, radio resource management, and mobility management are also required under LAA, but will not be discussed in this article. Readers who are interested in these LAA functionalities are referred to [5, 6].

Enhanced Licensed Assisted Access

eLAA is the evolution of LAA under development by 3GPP Release 14. eLAA adopts the same basic coexistence mechanisms in LAA, namely, DCS and LBT. An important improvement in eLAA is the support for LBT-based UL transmission in unlicensed bands. Key features of eLAA's UL design include the following.

Listen-Before-Talk: eLAA has two types of LBT-based channel access procedures for UL transmission: Type 1 and Type 2 [6]. The Type 1 procedure employs dynamic variable backoff based on contention window, while the Type 2 procedure does not.

eNB's UL Signaling: The implementation of eNB's UL signalling can be done on a different (either licensed or unlicensed) channel from the user's (so-called "cross-scheduling"), or it can be done on the same channel as the user's (so-called "self-scheduling").

MulteFire

MulteFire is the latest U-LTE technology that is being developed outside of 3GPP [7]. It is based on 3GPP Release 13/14 and supports both UL and DL transmissions in unlicensed spectrum. What is unique about MulteFire is that it solely relies on unlicensed spectrum for its operations without any anchor band in licensed spectrum. The stand-alone operation of MulteFire in unlicensed spectrum can help cellular operators or private network owners offer LTE services in areas where licensed spectrum is not available. Key features of MulteFire are:

•Two access modes, the public land mobile network (PLMN) access mode and the neutral host network (NHN) access mode. PLMN allows interworking between MulteFire and 3GPP PLMNs, which enables MulteFire cells to serve as additional RANs for PLMNs to extend their coverage, while NHN makes it possible to deploy a self-contained WiFi-like network in unlicensed bands using MulteFire.

•Reusing LBT channel access procedures as defined in 3GPP Release 13/14 (for LAA and eLAA).

•Enhanced discover reference signals (DRS), which is designed to incorporate a robust anchor carrier in unlicensed bands. DRS is introduced in 3GPP Release 12 and contains important synchronization and reference signals [17]. However, since LBT-based transmissions are opportunistic, it is possible that MulteFire will not be able to access the channel to transmit DRS for a long period of time. To address this issue, the MulteFire Alliance introduced an enhanced DRS method that incorporates some MulteFire-specific signaling mechanisms, including DRS measurement timing configuration (DMTC) and opportunistic DRS transmission (Fig. 5). DMTC is a transmission window (with a maximum duration of 10 ms) during which the serving MulteFire cell would transmit DRS to its users on certain subframes. DMTC occurs periodically every 40, 80 or 160 ms. Opportunistic DRS transmissions are done on specific subframes (subframe 0 in each radio frame of 10 ms) with LBT operation.

Table 2 summarizes key U-LTE standards that we discussed in this section.

Challenges and Open Problems

Before coming to the market, U-LTE still faces many technical challenges across different layers of the protocol stack. In what follows, we present open problems at the physical, MAC and upper layers for future research.

Support for Frequency Reuse: In licensed spectrum, LTE typically employs the same frequency band across multiple cells over an area (so-called "frequency reuse of one") to maximize

Standard	Coexistence mechanism	Key features	Strengths	Limitations	Key reference
LTE-U	DCS, CSAT	SDL transmission in unlicensed spectrum; operating in both licensed and unlicensed spectrum.	No change to LTE air interface protocol.	Cannot meet certain regional regulations; only supporting DL in unlicensed spectrum; may be less friendly to Wi-Fi if not properly designed.	[2–4, 11]
LAA	DCS, LBT	SDL transmission in unlicensed spectrum; operating in both licensed and unlicensed spectrum.	Meet global regulations; friendly to Wi-Fi .	Need to modify LTE air interface protocol; only supporting DL in unlicensed spectrum.	[5, 17]
eLAA	DCS, LBT	DL/UL transmissions in unlicensed spectrum; operating in both licensed and unlicensed spectrum.	Supporting both DL and UL in unlicensed spectrum; meet global regulations; friendly to Wi-Fi.	Need to modify LTE air interface protocol.	[6]
MulteFire	DCS, LBT	Largely using eLAA's channel access as baseline; solely operating in unlicensed spectrum.	No need of licensed spectrum; support both DL and UL in unlicensed spectrum; meet global regulations; friendly to Wi-Fi.	Need to modify LTE air interface protocol; may be less reliable due to lack of licensed anchor band.	[7, 8]

TABLE 2. A summary of U-LTE standards.

spectral efficiency. This is made possible by LTE's advanced inter-cell interference management. In unlicensed bands, there is no such interference management between LTE and WiFi. As a result, concurrent transmissions of LTE and WiFi are not possible. Coexistence mechanisms such as LBT can effectively achieve this purpose, but the downside is that LBT also prohibits potential frequency reuse among U-LTE nodes. Under current LBT design, neighboring LTE nodes are not allowed to transmit on a channel simultaneously due to contention-based channel access. This is rather limiting as it does not utilize the full potential of LTE. An interesting research problem is how to enhance LBT so that an LTE user can determine whether an active transmission is from an LTE system or a WiFi user.

Support for Multiple-User MIMO (MU-MIMO): MIMO is one of the key enablers for the success of LTE and LTE-A systems. LTE systems can operate in two MIMO modes: 1) single-user MIMO (SU-MIMO) (involving transmission between the base station and only one user at a time); and 2) MU-MIMO (involving simultaneous transmissions between the base station and multiple users). In 3GPP [5], it is recommended that UL MU-MIMO should be continuously supported in future eLAA. In licensed spectrum, LTE can benefit from MU-MIMO in both DL and UL directions since all transmissions are subject to centralized scheduling, but in unlicensed bands, UL MU-MIMO is not quite applicable to LBT-based U-LTE systems. For each UL/DL transmission, a subset of users are selected by MU-MIMO based on some user-grouping criterion. A successful UL MU-MIMO transmission requires that all selected users are able to transmit simultaneously on the same operating channel. However, this may not be possible as some users that are selected cannot access the channel at the time (due to neighboring WiFi transmissions or being in the back-off process). Thus, a more sophisticated user-grouping scheme (with consideration of user's channel access constraint) is needed.

Radio Resource Management (RRM): In the licensed spectrum, LTE's transmissions are continuous in time and subject to centralized scheduling. Radio resources are organized as a grid of resource blocks (RBs), spanning both time and frequency domains. An RB has a duration of 0.5 ms (termed a time slot) in time and 180 KHz in bandwidth. During every transmission time interval (TTI) (consisting of two contiguous time slots), the LTE eNB allocates the RBs to its users. Thanks to this fine-grained resource scheduling, LTE is able to achieve a more robust QoS guarantee and a higher spectral efficiency than other wireless technologies such as WiFi. But in the unlicensed spectrum, it appears to be difficult to retain these advantages.

First, transmissions in unlicensed bands are discontinuous and opportunistic (for systems using LBT). This significantly reduces the efficiency and flexibility of LTE's RRM. Second, the interference environment in unlicensed bands is much less predictable and controllable. The received interference level at a U-LTE node may increase suddenly due to opportunistic channel access from WiFi (Fig. 4) or transmissions from other U-LTE systems (e.g., LTE-U "on" periods). For U-LTE systems with a licensed anchor carrier (LTE-U, LAA and eLAA), how to optimally schedule radio resources across both licensed and unlicensed bands at the RB-level is a major challenge. For pure U-LTE systems (i.e., MulteFire), it is even more challenging to perform RRM.

Ensuring Fairness in Coexistence: A key design consideration for U-LTE is to ensure some "fairness" is achieved when it coexists with other systems. For LTE/WiFi coexistence, one fairness criterion that has recently gained attention is that a U-LTE system should not impact WiFi services more than an additional WiFi network supporting the same level of traffic load [5]. Prior research efforts (including [12]) mainly focus on throughput-based fairness. As demand on delay-sensitive mobile services grows, it is important to develop a more comprehensive fairness criterion with considerations of both throughput and delay. In particular, some of the coexistence mechanisms in Table 1 may deteriorate WiFi's delay performance. For example, if the duration of U-LTE's "on" period (under CSAT) or transmission burst (under LBT) were too long, WiFi would likely experience large packet delay and jitter. Therefore, better coexistence mechanisms (than those in Table 2) are needed when delay performance of WiFi is part of a fairness criterion.

Network Selection and Traffic Balancing: With the advent of U-LTE systems, it is plausible to envision U-LTE and WiFi cells to be densely deployed in the same area. In an LTE cell, we may see multiple versions of U-LTE standards from different providers operating at the same time.

It remains an important task to address the spectrum scarcity problem for licensed LTE. Given that unlicensed spectrum is being made available for commercial use, how to extend LTE to unlicensed spectrum has become a popular research topic in both academia and industry.

Likewise, WiFi networks may be installed with various 802.11 protocols and deployed by different operators. For users with the option of accessing multiple unlicensed networks (U-LTE or WiFi), the following problems arise:

- Network selection: from a user's perspective, how to choose the best network(s) to access based on its need?
- Traffic balancing: for network operators, how to assign users' traffic to different networks for the best network-user experience? Many practical issues need to be considered to address these questions, including pricing models, users' QoS requirements, and users' and networks' interface capabilities.

Conclusions

This article offers a concise review of recent advances in coexistence between LTE and WiFi in unlicensed spectrum. We showed that the fundamental challenge in such coexistence are the centralized characteristics of LTE. We reviewed a number of mechanisms that have been proposed to achieve fair coexistence and discussed their strengths and limitations. We also showed how industry incorporates these mechanisms into new standards. Many significant challenges still remain, both in theory and practice. We discussed a few open problems that we have encountered in our research and hope they can stimulate further study in this new and exciting area.

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