LTE-UNLICENSED: THE FUTURE OF SPECTRUM AGGREGATION FOR CELLULAR NETWORKS

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ABSTRACT

The phenomenal growth of mobile data demand has brought about increasing scarcity in available radio spectrum. Meanwhile, mobile customers pay more attention to their own experience, especially in communication reliability and service continuity on the move. To address these issues, LTE-Unlicensed, or LTE-U, is considered one of the latest groundbreaking innovations to provide high performance and seamless user experience under a unified radio technology by extending LTE to the readily available unlicensed spectrum. In this article, we offer a comprehensive overview of the LTE-U technology from both operator and user perspectives, and examine its impact on the incumbent unlicensed systems. Specifically, we first introduce the implementation regulations, principles, and typical deployment scenarios of LTE-U. Potential benefits for both operators and users are then discussed. We further identify three key challenges in bringing LTE-U into reality together with related research directions. In particular, the most critical issue of LTE-U is coexistence with other unlicensed systems, such as widely deployed WiFi. The LTE/WiFi coexistence mechanisms are elaborated in time, frequency, and power aspects, respectively. Simulation results demonstrate that LTE-U can provide better user experience to LTE users while well protecting the incumbent WiFi users' performance compared to two existing advanced technologies: cellular/WiFi interworking and licensed-only heterogeneous networks (HetNets).

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INTRODUCTION

With the proliferation of mobile devices and diverse mobile applications, wireless operators are experiencing phenomenal mobile data growth around the world. As reported from industry, global mobile traffic is more than doubling each year, and the mobile industry needs to prepare for 1000× as much traffic by 2020 [1]. Such 1000× mobile data demand for multimedia services has resulted in a huge strain on system capacity and makes quality of service (QoS) provisioning in future mobile communication systems challenging.

To meet such mobile data challenges, both industry and academia are on the hunt for advanced solutions to boost the network capacity while continually providing high-level user experience to their customers. Excavating more capacity on licensed spectrum is operators' first choice, as it provides secure, reliable, and predictable performance. For example, carrier aggregation (CA) technology [2], which is standardized in Long Term Evolution (LTE) Releases 10–12, aggregates multiple small band segments into maximum 100 MHz virtual bandwidth to achieve a higher data rate. Furthermore, to improve licensed spectrum efficiency, frequency reuse is enabled by deploying small cells overlaid with macrocells to provide high-speed localized services with enhanced intercell interference coordination (eICIC). The tiered deployment is called a heterogeneous network (HetNet) [3] in LTE Release 10, which conventionally refers to co-channel deployment of small cells sharing the same licensed spectrum with macrocells. In a dense deployment of HetNets, the licensed spectrum is easily congested with a large number of small cells, and sophisticated intercell interference management needs to be involved. This motivates operators to exploit the readily available unlicensed spectrum. Cellular/WiFi interworking [4] comes into being by allowing subscribers to adaptively use either licensed LTE or unlicensed WiFi networks for provisioning multimedia services. Although offering a capacity surge for operators, cellular/WiFi interworking requires communication management through asynchronous radio access technologies (RATs), and necessary modifications of the protocol stacks and interface functionalities. These requirements make resource allocation complicated and user service continuity hard to guarantee. In light of these issues, LTE-unlicensed (LTE-U) technology is initiated as part of LTE Release 13 to allow users to access both licensed and unlicensed spectrum under a unified LTE network infrastructure [5].

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LTE-U extends LTE to the unlicensed spectrum and aggregates the unlicensed spectrum with the licensed spectrum leveraging the existing CA technology. It can provide better coverage and larger capacity than cellular/WiFi interworking while allowing seamless data flow between licensed and unlicensed spectrum through a single Evolved Packet Core (EPC) network. For operators, LTE-U means synchronized integrated network management, the same authentication procedures, more efficient resource utilization, and thus lower operational costs. For wireless users, LTE-U means enhanced user experience; that is, higher data rates, seamless service continuity between licensed and unlicensed bands, ubiquitous mobility, and improved reliability).

While having a bright future, LTE-U is still in its infancy and faces many challenges before being brought to fruition. The primary challenge is the coexistence between LTE-U systems and the incumbent unlicensed systems, for example, user-deployed WiFi systems. Currently WiFi systems adopt a contention-based medium access control (MAC) protocol with a random backoff mechanism [6]. If left unrestrained, LTE-U transmissions can generate continuous interference to WiFi systems, resulting in unceasing backoff of WiFi nodes as the channel is detected to be busy most of the time. Hence, smart modifications to the resource management functionalities are indispensable on both the LTE-U and WiFi sides to achieve harmonious coexistence. Second, the traffic offloading issues in the LTE-U scenario need to be revisited. Unlike the conventional methods in cellular/WiFi interworking or HetNet deployment, traffic offloading in the LTE-U scenario needs to incorporate the user activities of other unlicensed systems, especially the widely deployed WiFi systems. To protect WiFi performance, LTE-U performance in unlicensed spectrum will inevitably fluctuate with WiFi activities, leading to considerable performance instability, which makes it challenging to provide LTE-U quality of service (QoS) guarantee. Thus, a trade-off between offloading LTE user data to unlicensed spectrum and ensuring the QoS of LTE-U subscribers should be made. Last but not least, unlike the licensed spectrum, different operators may access the same portion of unlicensed spectrum bands. Negotiation and coordination policies need to be deliberately designed to realize efficient inter-operator spectrum sharing.

In this article, we overview the LTE-U framework and investigate how the incumbent unlicensed systems will be impacted by LTE-U. Regulations, principles, and typical deployment scenarios are first introduced for harmonious unlicensed coexistence, followed by a summary of potential benefits from LTE-U. Then the above three challenges are elaborated and discussed together with related future research directions. Finally, simulations are conducted to illustrate LTE-U performance in terms of the average LTE user throughput and WiFi performance protection. The results are compared to those under conventional cellular/WiFi interworking and HetNet deployments.

Framework Overview for LTE-Unlicensed Technology

Unlicensed Spectrum

The unlicensed spectrum has enabled many low-cost wireless services from medical monitors to walkie-talkies and WiFi. The Federal Communications Commission (FCC) has released several bands for unlicensed commercial use, first in the 2.4 GHz industrial, scientific, and medical (ISM) band, and then in the 5 GHz unlicensed national information infrastructure (U-NII) band, and more recently in the 60 GHz millimeter-wave (mmWave) band. In 2014, the FCC voted unanimously to open up another 100 MHz of spectrum to meet the ever increasing demand for unlicensed wireless services as the first step and an additional 195 MHz in the next step, both in the 5 GHz band. The decision should not only promote the expansion of unlicensed WiFi networks, but also attract the attention of cellular operators to augment their services by using the complementary unlicensed bands.

The 2.4 GHz band is currently the most utilized band shared by different wireless users such as cordless phones, ZigBee, Bluetooth, and WiFi enabled devices. It provides broadband wireless access in local and personal areas. Compared to the 2.4 GHz band, the 5 GHz band is less congested and mainly used by WiFi (11a) devices. In addition, it has a shorter communication range due to higher pass loss but has wider available bandwidth.[1] Recently, there is growing interest from wireless carriers and vendors in utilizing a higher frequency band to achieve a higher capacity, for example, mmWave bands such as the 28 and 60 GHz bands.[2] Although currently used for local multipoint distribution service (LMDS), the 28 GHz band is quite underutilized, and the FCC is exploring whether this band should be exclusively licensed or shared with other users for efficient spectrum utilization. The unlicensed 60 GHz band has more abundant bandwidth than the 28 GHz band, making it feasible for bandwidth-intensive multimedia services [7]. However, the severe oxygen absorption and atmospheric attenuation at 60 GHz imposes great challenges in the design of physical layer specifications and air interfaces. Generally speaking, for the sake of clearer channel conditions, wider spectrum, and easier implementation, LTE-U currently focuses on 5 GHz bands to provide broadband multimedia services. Figure 1 shows the unlicensed spectrum layout in several different main regions at 5 GHz [8].

In the United States, the spectrum 5.15–5.35 GHz (UNII-1, UNII-2A), 5.47–5.725 GHz (UNII-2C), and 5.725–5.85 GHz (UNII-3) are currently used for unlicensed wireless access. New spectrum additions (i.e., UNII-2B and UNII-4) are being considered by the FCC to extend unlicensed use. In Europe and Japan, 5.15–5.35 GHz and 5.47–5.725 GHz spectrum are unlicensed for the wireless access system (WAS) including radio local area networks (RLANs). RLANs are intended for indoor environments such as houses and office buildings, of which one typical representative is the WiFi sys-

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[1] WiFi systems have 23 non-overlapping channels at 5 GHz compared to 3 non-overlapping channels at 2.4 GHz.

[2] The available bandwidth at mmWave bands is on the order of gigahertz.

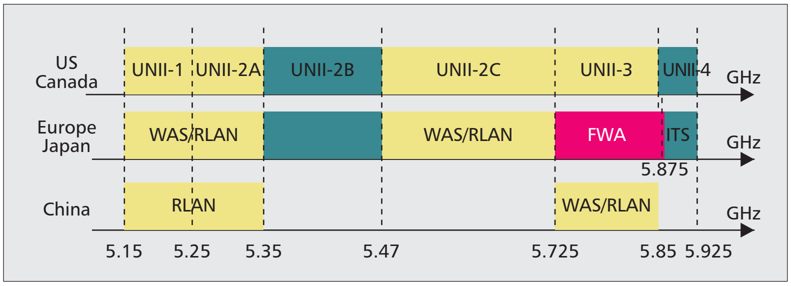

Figure 1. Unlicensed spectrum layout in different main regions at 5 GHz.

tem. Recently, the European Commission proposed allowing the unlicensed WAS/RLAN to use the 5.725–5.85 GHz spectrum, which is currently used for fixed wireless access (FWA) and intelligent transportation system (ITS). In China, the 5.15–5.35 GHz spectrum is only open for indoor unlicensed use (i.e., RLAN), while the 5.725–5.85 GHz spectrum can be used for both indoor and outdoor unlicensed systems [8].

Design Regulations and Principles

Although access to LTE over the unlicensed spectrum can be cost effective, some fundamental principles and regulations are imposed to guarantee harmonious coexistence between LTE-U and other incumbent systems. The regulated items encompass the transmission power, radar protection, channel access methods, spectrum aggregation, and so on [8].

Transmission Power: The first issue in the use of unlicensed spectrum is the regulation of transmission power. Such regulation is specified to manage the interference among unlicensed users. For instance, for indoor wireless access points (APs) in office buildings, which often fall within the 5.15–5.35 GHz spectrum band, the maximum transmission power is 23 dBm in Europe or 24 dBm in the United States, while outdoor usage (e.g., a hotspot picocell) allows a maximum of 30 dBm, which usually happens within the 5.47–5.85 GHz spectrum band. Besides the maximum transmission power, the 5.25–5.35 GHz and 5.47–5.725 GHz spectrum has mandated transmit power control (TPC) mechanisms. TPC reduces the power of a radio transmitter to the minimum necessary in order to avoid interference to other users and/or extend battery life while maintaining the link transmission quality.

Radar Protection and Dynamic Frequency Selection: Meteorological radar systems also operate in the 5 GHz unlicensed spectrum. Thus, the unlicensed devices may drop non-negligible interference on the normal radar transceiving if left without management. To better protect radars, an interference avoidance mechanism named dynamic frequency selection (DFS) is adopted in 5.25–5.35 GHz and 5.47–5.725 GHz spectrum. Under DFS, LTE-U devices periodically detect whether there are radar signals and will switch the operating channel to one that is not interfering with the radar systems upon detection. Additional regulations exist in different regions. For example, in Europe and the United States, unlicensed users are allowed in radar frequency, but are prohibited from accessing the configuration control settings that would allow disconnection from the DFS functionality or change to undesired frequency. But in Canada, unlicensed users are forbidden to access the 5.6–5.65 GHz spectrum, which is frequently used by the weather radar.

Listen Before Talk Feature: The LTE system is generally considered highly interference-resistant thanks to the centralized MAC and the use of powerful coding schemes in the physical layer. Many recent studies [9, 10] have shown that if LTE-U inherits the current MAC protocol without careful coexistence considerations, its operation would incur continuous interference to WiFi systems since WiFi adopts a contention-based MAC and will keep backing off when it detects LTE transmissions. To coexist with the incumbent unlicensed systems in a friendly and fair manner, LTE-U devices are required to detect before transmission whether the target channel is occupied by other systems at a millisecond scale[5]. This is referred to as clear channel assessment (CCA) or listen-before-talk (LBT), meaning that one LTE-U device can transmit only when no ongoing transmission is observed for a specified period. Although LBT is not required in North America for early LTE-U commercialization by leveraging the existing LTE Release 10-12 standards, it is widely expected to be put in the coming Release 13 to provide a global standard for future LTE-U implementation.

Licensed Assisted Access: Transmission on unlicensed spectrum is unstable since the nature of being unlicensed makes it hard to provision guaranteed QoS. To ensure the QoS and improve the user experience, the unlicensed use in LTE-U always comes with the use of licensed spectrum. Exploiting CA, component carriers in different frequency bands could be aggregated into wider virtual bandwidth to provide higher data rates. With CA, the control plane messages, including radio resource control signals and layer 1 signals, are always transmitted on the licensed band where QoS is ensured. The user plane data can be transmitted on either licensed or unlicensed carriers. In this fashion, the crucial information can always be transmitted with QoS guarantee, while the unlicensed carriers can provide opportunistic best effort data transmission enhancements.

Deployment Scenarios

Due to the transmission power limitations in unlicensed spectrum, the LTE-U technology is more suitable for a small area. Hence, the deployment of most interest is the operator-deployed small cell, which provides access to both licensed and unlicensed spectrum for indoor environment or outdoor hotspots. The aggregation of licensed and unlicensed spectrum can provide small cell users with high-speed and seamless broadband multimedia services. During transmission, a licensed carrier, called the primary component carrier (PCC), and several unlicensed carriers, called Secondary component carrier (SCCs), are accessible to one user at one time. According to the user traffic demand and cell load, configuration information can be conveyed via PCC to dynamically remove/add SCCs. In the remaining text, we refer to a carrier as a channel to avoid conceptual confusion.

There are two operation modes for LTE-U: supplemental downlink (SDL) and time-division duplex (TDD), as shown in Fig. 2. SDL mode is the simplest form of LTE-U where the unlicensed spectrum is only used for downlink transmission, as downlink traffic is typically much heavier than uplink traffic. In this mode, an LTE enhanced NodeB (eNB) can perform most of the required operations for reliable communications, including detecting the unlicensed channel occupancy. Typical applications for this mode are data-hungry downlink ones such as file/music downloading and online video streaming. In TDD mode, the unlicensed spectrum is used for both downlink and uplink, just like the LTE TDD system in licensed bands. TDD mode offers the flexibility to adjust the resource allocation between downlink and uplink, at the cost of extra implementation complexity on the user side, such as LBT features and radar detection requirements on the user equipment (UE). Applications for TDD mode are those that require high uplink rates such as FTP uploading and real-time video chatting.

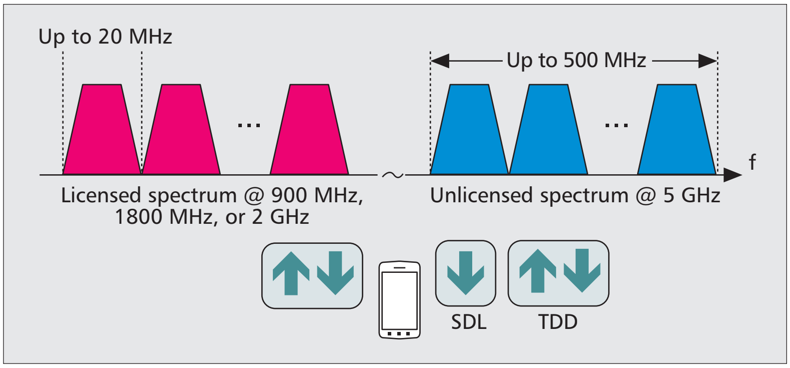

Figure 2. Two LTE-U operation modes: supplemental downlink (SDL) and TDD [5].

Potential Benefits from LTE-Unlicensed

Tremendous benefits can be achieved by extending LTE to the unlicensed spectrum. This section summarizes the perceivable and compelling benefits brought by LTE-U, compared to the WiFi system, which is the most commonly used unlicensed system nowadays.

Significant Boost in Data Rates through CA

As LTE-U leverages CA technology to aggregate both licensed bands and unlicensed bands, a wider bandwidth can be used to achieve higher throughput. In addition, LTE-U can provide higher spectrum efficiency in the unlicensed spectrum than WiFi systems. This is because LTE is a synchronous system and adopts scheduling-based channel access instead of contention-based random access. The centralized MAC can schedule multi-user transmissions based on the UE feedback information of the channel qualities, achieving multi-user frequency-selective diversity gain. Moreover, other advanced technologies adopted in a licensed LTE system can also be applied to the unlicensed spectrum. For example, the eICIC and coordinated multipoint (CoMP) transmission mechanisms enable different cells to coordinate when allocating resources (time, bandwidth, and power) so that cell edge users can benefit from the reduced interference and improved spectrum efficiency. These merits of LTE will bring in significantly increased data rates, which means smaller latency for the real-time applications, higher quality and stability for video streaming, and thus considerably better user experience.

Reliable and Secure Communication with a Solid Anchor in the Licensed Band

As noted above, the PCC only on which the important control messages are transmitted is always located in licensed spectrum, where the QoS can be ensured. The licensed LTE has defined nine QoS class identifiers for different application types, among which the control signalings are granted the highest priority. This means that whatever the unlicensed channel conditions are, the control plane messages are transmitted properly between the base stations (BSs) and UEs. Since licensed spectrum and unlicensed bands are integrated on the same small cell BS, the network side has more global information, including the traffic load of each LTE-U BS, the LTE-U network topology, interfering WiFi locations, and so on, thus being able to better facilitate the opportunistic unlicensed access. But for WiFi systems, performance instability can be a serious problem since current WiFi is not efficient when the network is heavily loaded, especially when the number of contending users increases. Besides, LTE performs better than WiFi in terms of user authentication and authorization techniques, providing subscribers with more secure transmissions.

Seamless Mobility and Coverage

With LTE-U, the same LTE access methods are used on both licensed and unlicensed spectrum, so UEs are operated within a unified network architecture. A unified architecture first means the same core network, and the same integrated authentication, security, and management procedures. Considerable overhead in the unlicensed spectrum can be saved by this unification since control plane signalings can be transmitted over the licensed bands, which can minimize the access/initiation time when UE first accesses the unlicensed spectrum. Second, a unified architecture means synchronization on both spectrum types, through which interference bursts can be handled better. Third, the PCC in the licensed spectrum can always provide ubiquitous coverage for one UE. When a UE moves out of the coverage of a small cell BS, only horizontal handover is needed between small cell and macrocell, and the UE's ongoing session can be switched as seamlessly as possible without any interruption. Last but not least, LTE also offers a better and more robust air link structure designed specifically for mobility. All the above features can be contrasted with the interworking system between LTE and WiFi. The interworking system is more implementation-complex, which requires many modifications in the proto-

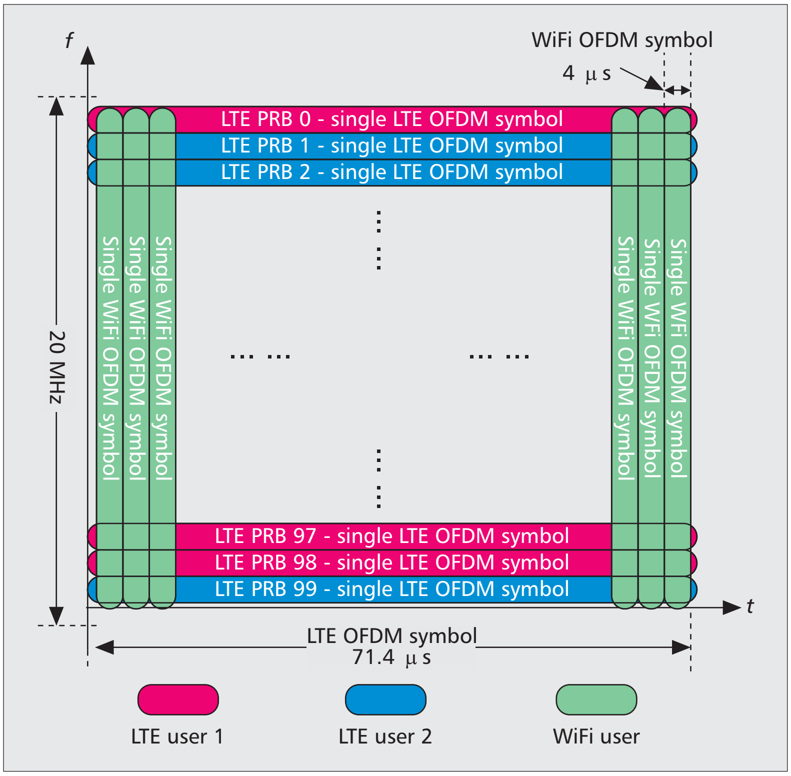

Figure 3. PHY and MAC comparisons between LTE and WiFi systems in both time and frequency domains [9]. For a 20 MHz LTE channel (one carrier), its effective transmission bandwidth is 18 MHz. One PRB is 180 kHz. Thus, a 20 MHz LTE channel has 100 PRBs, which can be allocated to multiple users (users 1 and 2) simultaneously. In contrast, all the bandwidth in a WiFi system can only be occupied by one user within each 4 µs OFDM symbol.

col stacks and interfaces of both systems. Different synchronization and authentication mechanisms may lead to more overhead and latency as one UE has to perform vertical handover when moving out of WiFi coverage. As a result, service interruption will probably be perceived at the UE side. Therefore, LTE-U has considerable advantages in preventing the UE from perceiving the impact of mobility.

Harmonious Coexistence with Incumbent Systems

The introduction of LTE-U is regulated to take considerable care to protect the performance of incumbent systems, especially WiFi systems. In May 2013, the High Efficiency WLAN (HEW) Study Group (SG), also known as 802.11ax SG within the IEEE 802.11 Working Group, started to consider improving the spectrum efficiency to enhance the WiFi system throughput in dense deployment scenarios. Many telecommunication companies, including Huawei, Qualcomm, Intel, and so on, have been devoted to the development and standardization process of 802.11ax. In particular, Huawei has presented a WiFi prototype that can achieve as high as 10 Gb/s data speed in the 5 GHz band. If LTE-U small cells exist in such a dense deployment scenario, it is very likely that one LTE-U small cell has to share the same channel with WiFi systems. By carefully protecting the WiFi performance via LBT, LTE-U is able to achieve harmonious coexistence when sharing the same channels with WiFi. The LBT feature will not allow LTE-U transmissions to occupy the channel all the time, but to share the resources with WiFi in a fair and friendly manner. Some preliminary research results [11] have demonstrated that through deliberately designing resource sharing algorithms at the LTE-U side, one LTE-U small cell can be just as good a neighbor to a WiFi network as WiFi itself, and sometimes even better. The detailed resource sharing methodologies are elaborated later.

Challenges and Potential Research Directions

While being a groundbreaking innovation to meet the explosively increasing mobile data demand, LTE-U still faces quite a few challenges before coming to fruition. This section identifies several critical challenges in LTE-U evolution, and provides some inspirations toward future research directions as well as the related works.

Challenges with LTE-U Implementation

Enabling LTE-U in unlicensed shared spectrum still faces some critical challenges. The primary indispensable challenge is the coexistence mechanism design among different RATs. The barrier to efficient coexistence is the lack of inter-RAT coordination and mutual interference management when sharing the same unlicensed spectrum. Currently, the resource allocation functionalities for different RATs are performed independently; the interference management mechanisms are RAT-specific with significantly different MAC and PHY protocols, making inter-RAT coordination quite challenging. LTE and WiFi coexistence is given below as an example.

The LTE system adopts a centralized MAC protocol, which always allocates one resource unit to the user that can maximize the target metric in every subframe.[3] WiFi systems use a totally different MAC protocol based on the distributed coordination function (DCF) [12]. DCF is a contention-based mechanism that adopts carrier sense multiple access with collision avoidance (CSMA/CA). Before transmission, the node will first listen to the intended channel. If the interference level exceeds a threshold, the node will back off for a random time. In this manner, the collision probability is reduced at the expense of lower channel utilization. Besides the MAC protocol, the two systems have different physical layer features, as shown in Fig. 3 given by [9]. LTE employs orthogonal frequency-division multiple access (OFDMA) in the physical layer. The system bandwidth, usually 1.4–20 MHz without CA and up to 100 MHz with CA, is divided into a series of physical resource blocks (PRBs), each composed of 12 OFDMA subcarriers. Different PRBs can be scheduled to different users in the same subframe, thus achieving multi-user diversity gain. The WiFi system adopts orthogonal frequency-division multiplexing (OFDM) in the physical layer; how-

[3] One subframe is the minimum resource allocation time unit in LTE systems with a duration of 1 ms.

ever, it allows only one user to occupy the whole channel at one time, the bandwidth of which is usually 20 MHz and can reach up to 160 MHz with channel binding. The OFDM symbol durations are also different in the two systems. For LTE the symbol duration is 71.4 μs, while WiFi has a finer granularity of 4 μs. In light of the aforementioned differences between the two systems, intelligent modifications are required in the design of radio resource management to allow harmonious coexistence of LTE and WiFi.

The second challenge lies in user traffic offloading from licensed spectrum to unlicensed spectrum within a single operator. Traffic offloading issues have been extensively studied mainly in the context of two deployment scenarios:

- Traditional co-channel HetNets, where macrocells and small cells both utilize LTE technology and share the same licensed spectrum
- Cellular/WiFi interworking, where users have both LTE and WiFi air interfaces, and optimize the traffic load balancing between the two networks in either single-radio mode or multi-homing mode [4]

LTE-U traffic offloading is subject to the unlicensed regulations, thus presenting unique features. The above two scenarios mostly focus on resource management for users within the same system — either the LTE system or the integrated interworking system — whereas traffic offloading in the LTE-U context should take into consideration the user activities from other independent unlicensed systems in order to protect their performance. Due to LBT features, one LTE-U small cell may not be able to occupy the unlicensed spectrum for a certain period even if it is needed by LTE-U users. Hence, the LTE-U performance in unlicensed bands is time-varying and heavily dependent on other systems' channel access activities. Consequently, a dilemma arises: on one hand, an LTE-U small cell tends to assign more users to the unlicensed spectrum to reduce interference to the macrocell users; on the other hand, user performance on the unlicensed spectrum varies a lot, thus making it hard to provision QoS guarantee. Therefore, trade-offs need to be made to provide LTE users with optimized traffic dispatch over different bands [13].

Last but not least, the bandwidth sharing nature of the unlicensed spectrum makes it possible for different operators to access the same portion of bandwidth, which makes LTE-U resource management more complicated and challenging. As different operators have equal priorities on unlicensed spectrum, uncoordinated resource management will lead to chaotic inter-operator interference when two operators happen to choose overlapped frequency bands. Therefore, negotiation and coordination policies are needed to either avoid the mutual interference by assigning orthogonal bands to different operators or carefully mitigate the inter-operator interference if nonorthogonal bands are used.

Research Topics and Related Work

In light of the aforementioned challenges, this subsection first investigates the mutual interference management between LTE-U and WiFi systems from the perspectives of interference avoidance and interference mitigation, respectively. Then resource allocation issues are covered from the LTE-U side including intra-operator traffic offloading and inter-operator spectrum sharing.

Dynamic Channel Selection — As the unlicensed spectrum is bandwidth-rich, the large number of available unlicensed channels offers high probability for an LTE-U small cell to find an unused channel with very low-level interference. By enabling small cells to choose the cleanest channel based on the LTE and WiFi measurements, the interference can be avoided not only among small cells but also between the LTE and WiFi devices. A pioneering work by Qualcomm [11] presents a simple yet effective policy for dynamic channel selection. As the interference level in the unlicensed channels may change due to the independent WiFi operations, the interference measurements are performed at both equipment initialization and periodically during operation. If the interference in the occupied channel exceeds a predefined threshold, the LTE-U transmissions will switch to a new channel with the least interference. The interference measurements should involve both the network and UE sides. With the assistance of UE's feedback information, for example, channel quality indicator (CQI), the measurement accuracy can be significantly improved and the hidden terminal problem effectively avoided. Besides, in [10], F. M. Abinader Jr. *et al.* also discuss how to leverage the existing embedded techniques in both LTE and WiFi systems to enable dynamic channel selection. The adaptive bandwidth channel allocation offered by LTE and the least congested channel search (LCCS) mechanism adopted in WiFi are suggested to facilitate channel selection.

There are generally two levels of interference detection [11]. In the first level, the interference is simply measured by energy detection, which is agnostic to the type and number of the interferers. In the second level, advanced RAT-specific measurements can be performed to improve the detection sensitivity by collecting the type and quantity information of the interfering sources. For example, WiFi preambles, which are originally used in WiFi by receivers to identify and synchronize with the transmitters, can be detected by the small cell to estimate the number of neighboring WiFi APs. Similarly, the LTE control signalings from neighboring LTE-U cells can also be used for improved detection.

Co-Channel Coexistence with WiFi Systems — Although the available unlicensed bandwidth is relatively abundant, it is still possible that sometimes no clean channel is available, so LTE-U and WiFi have to share the same channel. This may happen due to an ultra-dense small cell deployment, bandwidth range regulations for one operator, or limitations of BS CA capabilities. Since LTE has shown dominant system performance over WiFi in the co-channel scenario, some restrictions need to be imposed on LTE resource allocation in order to protect the WiFi performance. In some regions such as Europe, Japan, and India, LBT features are mandated that require physical

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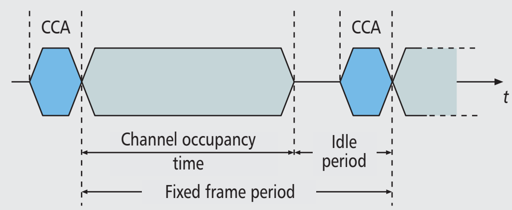
The basic idea of CSAT is to define a TDM cycle during which the LTE-U small cell transmits in an on and off style, that is, a fraction of the cycle is used for small cell transmissions and the rest is left for transmissions of other technologies.



(a)

Parameter	Requirement
Clear channel assessment (CCA) time	Minimum 20 μs
Channel occupancy time	Minimum 1 ms, maximum 10 ms
Idle period	Minimum 5% of the channel occupancy time
Fixed frame period	Channel occupancy time + idle period
CCA energy detection threshold	Assuming receiver antenna gain is 0 dBi Threshold = –73 dBm/MHz + 23 – *PET*

(b)

Figure 4. ETSI specifications on LBT time-based frame structure [8]: a) ETSI LBT frame structure; b) key parameters of the frame structure.

layer modifications on the symbol waveform design. In other regions such as the United States, China, and South Korea, LBT is phase-wise not required for early commercialization although it will eventually be adopted. Even so, channel listening still plays a key role in resource allocation for such areas. In the following, some resource allocation mechanisms are discussed with and without LBT features from the time sharing and power control aspects.

LBT requires the LTE-U device to periodically stop the channel occupancy and detect the activities of other channel occupants on a scale of milliseconds. Figure 4 shows the LBT specification for timeframe-based device proposed by the European Telecommunications Standards Institute (ETSI)[8]. The key parameters are summarized on the right. Before transmission, the LTE-U UE or BS needs to first listen to the target channel to detect the energy level for a period called clear channel assessment period. Only if the interference level is below a predefined threshold, the UE or BS can occupy the channel for a fixed time period, referred to as channel occupancy time. The idle period should be at least 5 percent of the channel occupancy time. The threshold for interference power detection is dependent on the equivalent isotropically radiated power (EIRP) of the interfering transmitters, denoted as *PET* in the right table. Another LBT-based mechanism is proposed in [14] where sensing and backoff functions similar to WiFi DCF are introduced on top of the original LTE MAC scheduling. No fixed duty cycle exists; instead, the BS or UE will sense the channel whenever it has packets to transmit and starts transmission after the backoff time if the channel is available. Moreover, request-to-send/clear-to-send (RTS/CTS) functions can also be involved to reserve the channel by transmitting the CTS packet after sensing the channel. Compared to duty cycling, the second mechanism is more flexible in terms of dynamic channel sharing, thus being more beneficial to WiFi systems. However, this comes at the cost of higher implementation complexity.

For early LTE-U commercialization without LBT requirements, several mechanisms have been proposed to fairly manage resource sharing between LTE and WiFi. Qualcomm has proposed to adopt carrier-sensing adaptive transmission (CSAT) for LTE-U MAC scheduling [11]. The basic idea of CSAT is to define a TDM cycle during which the LTE-U small cell transmits in an on and off style, that is, a fraction of the cycle is used for small cell transmissions and the rest is left for transmissions of other technologies. The cyclic on/off ratio can be adaptively adjusted based on the sensed channel activities of the other technologies during the off period. CSAT can be implemented with the existing LTE standard (e.g., Release 10), which enables dynamic carrier (de)activation via MAC signalings on a milliseconds scale, and is shown to have impact on the neighboring WiFi APs no worse than another neighboring WiFi AP. However, since the duty cycle is usually set to a few hundreds of milliseconds to ensure a long enough sensing duration, the delay perceived by the LTE-U users is considerably increased. A similar mechanism called LTE muting is proposed in [9], where LTE is silent in n of every 5 subframes to abdicate the channel to WiFi users. Almost blank subframes (ABSs) in the existing LTE standard can be exploited to realize the muting mechanism. ABS is originally intended for interference coordination in HetNets by muting the transmission power[4] of the small cells in certain subframes so that less interference is caused to macrocells. Thus, in LTE-U scenarios, ABSs can be used to control the LTE activities in unlicensed spectrum [10]. LTE muting can effectively reduce the LTE user delay as there is no big time gap between two transmissions. However, the short sensing period can lead to inaccurate channel sensing results, thus severely impacting the adaptability to the time-varying WiFi activities.

In addition to the time sharing methods, LTE transmit power control can be an alternative to assist LTE/WiFi coexistence in the uplink. The conventional uplink power control is based on the UE path loss, which does not take the WiFi activities into consideration. Cell edge UEs may have a high transmit power, thus affecting the WiFi transmissions in the vicinity. An improved uplink power control method is proposed in [15] to involve the LTE interference measurements in power control decisions. As UEs perceiving high WiFi interference are more likely to cause

[4] Not completely muting since some important control signalings are still transmitted in ABSs such as reference symbols and synchronization symbols.

high interference to others, the proposed interference-aware power control imposes a decrease in the operating power point in proportion to the interference level. Consequently, the WiFi performance is improved at the cost of acceptable decrease in unlicensed LTE uplink performance.

In summary, interference detection is a crucial issue for LTE/WiFi coexistence mechanism design with or without LBT features, as it is decisive in the amount of resources that the WiFi systems can obtain. Meanwhile, to keep the LTE user delay under a desired level, trade-offs should be addressed between the interference detection accuracy (sensing-period-dependent) and LTE user experience. In addition to the mechanism design based on the sensing results, mutual interference modeling for LTE/WiFi coexistence is another interesting topic that can offer us an effective tool for estimating the coexistence performance without running the systems in practice and help us understand the essence of the testing results.

Intra-Operator Traffic Offloading — As aforementioned, the traffic offloading in LTE-U context should deliberately incorporate the impact of WiFi activities. Mutual interference modeling is an unavoidable issue in designing the optimal traffic offloading strategy to unlicensed spectrum. Besides, the trade-offs between the licensed co-channel interference mitigation and the QoS provisioning of LTE-U users should also be considered. There have been several research works targeting traffic balancing in LTE-U scenarios. For example, a framework for femtocells to access both licensed and unlicensed bands is proposed in [13] where femtocells share the same unlicensed channel with WiFi systems and access the unlicensed bands based on duty cycling. By modeling the WiFi exponential backoff mechanism into a 2-dimensional Markov chain, the throughput performance of both LTE and WiFi cells is analytically derived and verified through system-level simulations. Simulative comparisons are also conducted to demonstrate the dual-band access strategies outperform the carrier WiFi and conventional licensed-only cases in terms of total cellular and WiFi throughput. In the extended work, an optimal traffic balancing strategy is proposed to maximize the total user satisfaction of femto and WiFi users while keeping the perceived interference of macro users below the desired level. The work considers the balance between licensed co-channel interference mitigation and the LTE-U users' satisfaction as well as the mutual interference between femtocells and WiFi systems.

For the intra-operator traffic offloading, future efforts could be focused on investigating the mutual interference modeling when different coexisting mechanisms are adopted, and considering the inter-femtocell interference in dense deployment scenarios.

Inter-Operator Spectrum Sharing — When LTE-U small cells of multiple operators exist in the same region, inter-operator coordination and negotiation is required.

To the best of our knowledge, there are currently no existing works that investigate inter-operator spectrum sharing in the LTE-U scenario, but spectrum sharing among operators in licensed bands has already been studied, which can provide valuable insights for inter-operator spectrum sharing in the LTE-U scenario. If the available spectrum is abundant, different operators can select different clean channels to access, which can be referred to as orthogonal inter-operator spectrum sharing. In dense deployments where multiple operators have to use the same channel, referred to as non-orthogonal inter-operator spectrum sharing, two possible approaches can be exploited to mitigate the inter-operator interference. Time sharing is the first approach, where different operators can access the channel in different time durations. The fractional frequency reuse (FFR) approach may be a second approach where small cell users of different operators are allowed to transmit on the channel simultaneously if they are close to their respective cell centers; meanwhile, the cell edge users of different operators will access the channel in a time-sharing way. The pros and cons of these two approaches can be summarized as follows: compared with the time-sharing approach, the FFR approach is more spectrum-efficient and flexible in resource allocation, but at the cost of higher computational complexity and control overhead in order to mitigate the interference caused by frequency reuse among different operators.

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Performance Evaluation

In this section, simulations are conducted to demonstrate the advantages of LTE-U in LTE performance enhancements and WiFi performance protection. The two aforementioned conventional deployment patterns, cellular/WiFi interworking and HetNets (with licensed bands only), are also simulated for comparison. In LTE-U, dynamic channel selection and co-channel coexistence mechanisms are implemented. Three co-channel coexisting mechanisms (i.e., no coordination, ETSI duty cycling, and CSAT[5]) are evaluated, respectively.

The network topology shown in Fig. 5 with SDL mode is considered. The cellular network is a two-tiered network, where macrocells and outdoor picocells share the same 20 MHz licensed spectrum. The inter-site distance of macrocells is 500 m. For each macrocell, 10 picocells and 10 user-deployed WiFi APs are randomly distributed in a cluster with a radius of 75 m, and the inter-pico-BS and inter-AP distances are both at least 10 m. The clustered distribution is adopted to simulate a dense deployment scenario where co-channel coexistence mechanisms have to be utilized. Both picocells and WiFi APs can access 2×10 MHz unlicensed bandwidth at 5 GHz. 50 LTE-U users and 50 WiFi users are dropped randomly within 90 m of each cluster center, and 50 macrocell users are dropped randomly in the remaining space of each macrocell. A full buffer traffic model is considered for each user.

In cellular/Wi-Fi interworking deployment, all the picocells in Fig. 5 are replaced with operator-deployed WiFi APs (referred to as cellular WiFi in the following), and cellular WiFi users

[5] In the simulations, the on/off ratio is calculated in the following way. During the off period, a fixed interference threshold is first predefined for the detection of the WiFi user activities. For one LTE-U BS, if the received interference from WiFi users exceeds the threshold on the target channel, the WiFi system is considered as active. Before one TDM cycle starts, the LTE-U BS first summarizes the active time of the WiFi system during the off period in the previous 10 TDM cycles, then calculates the ratio between the summation and the total off period in the previous 10 TDM cycles. The achieved ratio is used as the portion of off period for the LTE-U BS in the coming TDM cycle.

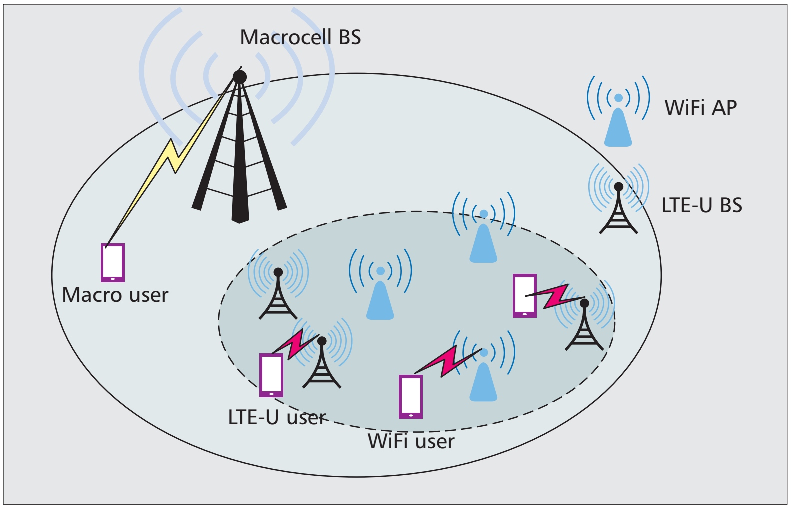

Figure 5. Simulated LTE-U network topology.

offload their services to the cellular WiFi APs. In HetNet deployment, all the picocells can only operate on the licensed bands. The comparison results are presented in Fig. 6 in terms of average user throughput in both licensed and unlicensed spectrum for LTE small cells (i.e., cellular WiFi, HetNet picocells, and LTE-U picocells) and user-deployed WiFi networks. Note that the operator-deployed WiFi user, HetNet small cell user, and LTE-U user are collectively called LTE small cell subscriber in Fig. 6.

In Fig. 6, the actual value for the user-deployed WiFi user throughput in case 1 is 3.5712 Mb/s. The other throughput values shown in Fig. 6 are all normalized by 3.5712 Mb/s. From Fig. 6, it can be observed that in case 1, cellular WiFi and user-deployed WiFi have equal user throughput due to the same number of users and APs as well as the same RAT. In case 2, the user throughputs of both networks have increased more than two times. The reason is that HetNet small cell users access the licensed spectrum based on the centralized LTE MAC protocol, which has significantly higher spectral efficiency than DCF mechanism. As LTE small cells use orthogonal spectrum with WiFi, the WiFi user throughput is doubled without the interference from LTE.

Furthermore, in the introduced LTE-U deployment without coexistence mechanisms (i.e., case 3), the user-deployed WiFi performance is severely blocked by the unlicensed LTE transmissions and diminishes to 0.32 times that in case 1. When the coexistence mechanism of duty cycling is implemented (i.e., case 4), although the LTE unlicensed user throughput decreases, it is still approximately 34 percent higher than that in case 1. More importantly, the WiFi user throughput in case 4 increases significantly compared to that in case 3 and becomes even 22 percent better than that in case 1. This indicates that compared to interworking and HetNets deployment, LTE-U with coexistence mechanisms can achieve considerably better LTE small cell subscriber throughput; meanwhile, one LTE-U small cell can be as good a neighbor to a WiFi network as WiFi itself and sometimes even better. Moreover, in case 5 where CSAT is adopted, the LTE-U unlicensed user throughput is slightly increased, while the WiFi user throughput is slightly decreased compared to case 4. This is because the duty cycling mechanism adopts LBT features, which can better decrease the collision probability with the WiFi users. Consequently, more resources can be occupied by WiFi networks, leading to higher WiFi user throughput.

Conclusions and Future Research

In this article, we have presented an overview of the emerging LTE-U technology, which extends LTE over the unlicensed spectrum band to fulfill the ever increasing mobile traffic demands. The regulations, principles, and typical deployment scenarios for LTE-U have first been elaborated, followed by the potential LTE-U benefits. Furthermore, three challenging issues have been identified in bringing LTE-U to reality, and related research directions have been discussed together with some existing works. Finally, simulation results have been presented to demonstrate that LTE-U can achieve higher throughput for small cell users while protecting WiFi network performance well.

For future research, three aspects are of the most interest:
- Analytical modeling and theoretical studies are essential to find an effective and tractable mutual interference model for LTE/WiFi coexistence under different coexisting mechanisms.
- The inherent PHY/MAC differences between LTE and WiFi systems need to be considered in modeling the mutual interference.
- The intercell interference between macrocells and between LTE-U small cells should be incorporated in a dense deployment scenario.

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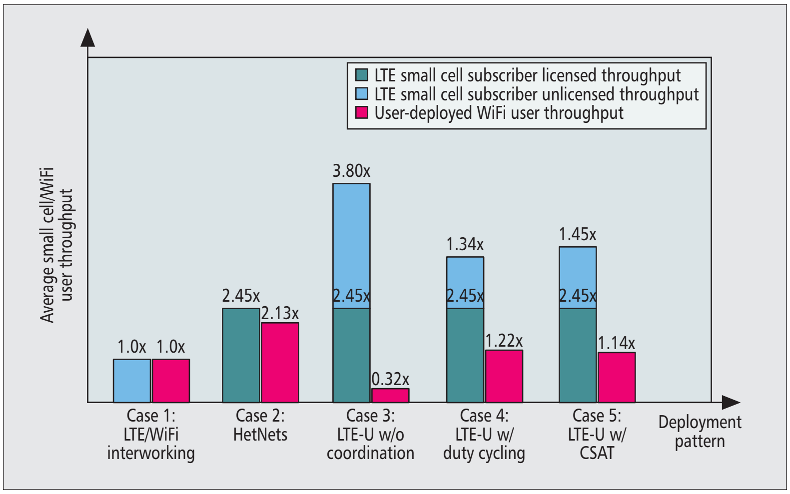

Figure 6. Average user throughput comparisons in both licensed and unlicensed spectrum under different deployment patterns.