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LTE in the Unlicensed Spectrum: A Survey

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ABSTRACT
Fueled by the increasing popularity of handheld mobile devices with powerful data processing capabilities, the wireless industry is witnessing an avalanche of mobile traffic. This unprecedented escalation has imposed significant challenges due to the limited licensed spectrum for cellular networks. Any effort to achieve capacity growth through network densification will face the challenge of severe inter-cell interference. Among the most effective solutions to this issue is to make the best use of all spectrum types through matured technology. Long-term evolution (LTE) access to unlicensed spectrum is considered one of the latest groundbreaking innovations to provide high-performance and a seamless user experience under a unified radio technology by extending LTE to the readily available unlicensed spectrum. In this article, we introduce the dawn of LTE access to unlicensed spectrum as a boon to the spectrum scarcity problem. Then, we explore deployment scenarios for LTE in unlicensed spectrum. We further identify key issues in bringing LTE unlicensed spectrum access to reality, together with other technologies for accessing unlicensed spectrum, specifically Wi-Fi. Finally, we discuss some existing coexistence mechanisms for successful, harmonious deployment of LTE and Wi-Fi in the same unlicensed band.

KEYWORDS
Coexistence; LAA; LTE; LTE-U; Spectrum management
Wi-Fi

1. INTRODUCTION

Enormous growth in data traffic due to the proliferation of smartphones and diverse connected devices has challenged network operators to increase capacity. A forecast by Cisco Systems, Inc. [1] shows that traffic growth will nearly exceed 8 fold between 2015 and 2020. However, due to the limited nature of licensed spectrum, it is impossible to allocate exclusively new spectrum to fulfil demand. Increasing spectrum usage through spectrum sharing and cell densification has become promising solution these days. Hence, two big wireless standard groups, the 3rd Generation Partnership Project (3GPP) and the Institute of Electrical and Electronics Engineers (IEEE 802.11), are actively investigating solutions. To date, the 3GPP group is investigating small cell deployment in LTE Release 12 and beyond [2]. Similarly, the IEEE 802.11 working group is studying IEEE 802.11ax to enhance system performance of Wi-Fi in dense deployment scenarios [3].

In the history of wireless communications, sustained spectral efficiency improvement has been achieved by means of several advanced techniques, such as multiple-input, multiple-output (MIMO) [4], interference mitigation techniques [5], cooperative multipoint, coordinated beamforming, power allocation, relay, etc. However, such improvements seem to be limited by complexity, spectrum scarcity, and increasing deployment costs. Mobile traffic offloading has come across as a complementary network technology to address part of the traffic demand. Small cell networks [6] and dynamic spectrum access (DSA) [7] techniques are two main technologies lying behind the empowerment of mobile traffic offloading. Despite numerous capacity and spectrum-efficient technologies, spectrum demand is so extreme that joint operation of LTE and Wi-Fi is expected. LTE is the preferred choice for traffic offload due to its optimal usage of radio resources. Low deployment costs and broad adoption of Wi-Fi make it competitive, despite its lower radio resource–usage efficiency. As the first part of heterogeneous technology coexistence, cellular/Wi-Fi interworking [8] was initiated by allowing subscribers to adaptively use either licensed LTE or unlicensed Wi-Fi networks in Release 12. Later on, the several technique of inter working ranges from Non-Seamless WLAN Offload (NSWO) [9], to loosely coupled methods such as S2b [9], to somewhat more advanced methods such as LTE WLAN Radio Level Integration with IPsec Tunnel (LWIP) [10], to ultimately LTE-WLAN aggregation (LWA) [11]. WLAN finally becomes fully integrated into cellular operator's network with LWA. Even though cellular/Wi-Fi interworking does not comprise of any overlapped spectrum band between both technologies, spectrum allocation requires communications management through asynchronous radio access technologies

Table 1: Global 5-GHz band status [12]

Frequency	Band	US	Europe	Japan	China	Korea
5150–5250	UNII-1	Indoor outdoor	Indoor	Indoor satellite	Indoor outdoor	Indoor
5250–5350	UNII-2A	Indoor outdoor DFS,TPC	Indoor outdoor DFS,TPC	Indoor outdoor DFS,TPC	DFS,TPC	DFS,TPC
5350–5470	UNII-2B	Under study	Under study	No	Under study	Under study
5470–5650 5650–5725	UNII-2C	Indoor/outdoor DFS,TPC	Indoor/outdoor DFS,TPC	Indoor/outdoor DFS,TPC	In consideration	Indoor/outdoor DFS,TPC
5725–5825	UNII-3	Indoor/outdoor	Indoor/outdoor	No	Indoor/outdoor	Indoor/ outdoor
5825–5850	UNII-3	Indoor/outdoor	Indoor/outdoor	No	Indoor/outdoor	Under study
5850–5875	UNII-4	Under study	Indoor/outdoor	No	Under study	Under study
5875–5925	UNII-4	Under study	Under study	No	Under study	Under study

UNII = Unlicensed National Information Infrastructure, DFS = dynamic frequency selection, TPC = transmission power control.

(RATs), together with necessary modifications of the protocol stacks and interface functionalities. These necessities make resource allocation problematic, and the quality of the user services hard to guarantee.

In light of these issues, researchers discovered a globally available, abundant, underutilized spectrum below 6 GHz as shown in Table 1. Mostly, Wi-Fi (802.11a, 802.11n, and 802.11ac) and some other applications, such as cordless phones, perimeter sensors, and radar, are using this spectrum. Due to the following relevant aspects, 5 GHz is expected to be an appropriate unlicensed band [13].

(1) 500 MHz of unlicensed spectrum is available for free.
(2) The spectrum is available on a global basis with very similar band plans.
(3) Wider bands are suitable for efficient sharing among multi-users.
(4) 5 GHz is less crowded than 2.4 GHz with existing residential, and even public, deployment.
(5) Higher 5 GHz spectrum and lower transmit power regulations make it ideal for deployment of small cells with good channel propagation performance.

Hence, LTE in unlicensed technologies have been introduced in forms of LTE-U, standardized by the LTE-U Forum [13], and LAA, standardized by 3GPP [14] to allow users to access both licensed and unlicensed spectrum under a unified LTE network infrastructure. LTE-U was first proposed by Qualcomm in December 2013 to enable 4G LTE in 2.5 GHz and 5 GHz unlicensed bands as a secondary carrier for downlink-only and/or uplink and downlink 4G. Later on [15], almost all cellular vendors, such as Qualcomm, Ericsson, Huawei, and Nokia increased interest in the deployment of LTE using unlicensed spectrum, as shown in Figure 1. The fundamental concept of LTE unlicensed technologies extend the LTE

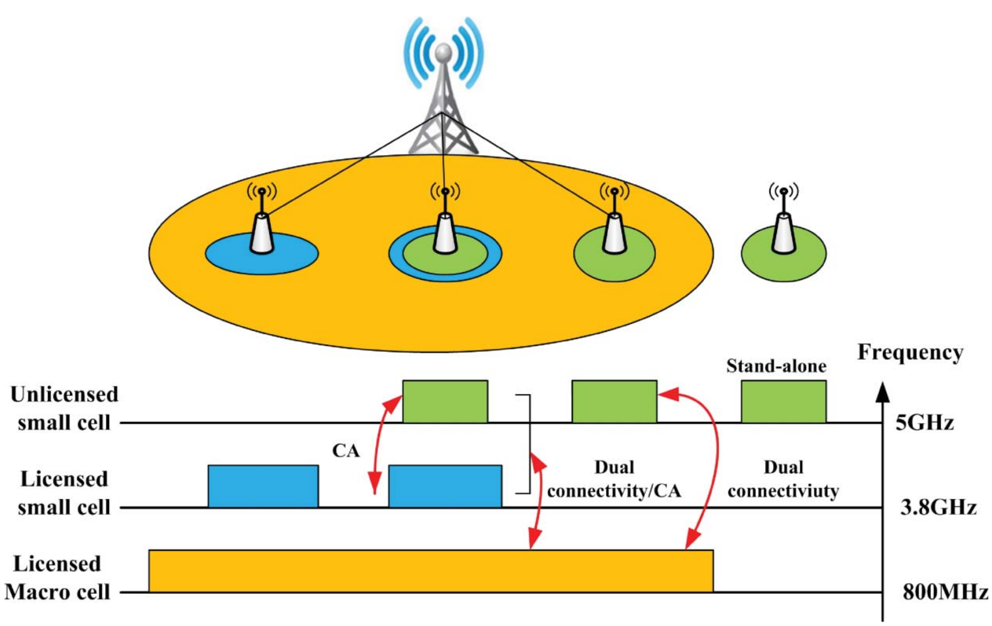


Figure 1: LTE using unlicensed spectrum

radio frequency to unlicensed frequency band of 5 GHz band which is specified by 3GPP as band 46 [14]. In LTE unlicensed technologies, licensed carrier holds critical control signaling, mobility, and high-quality user data demanding quality of service (QoS), whereas less critical data is carried over the unlicensed band. LTE unlicensed technologies offload best-effort traffic through the carrier aggregation framework already defined under LTE Advanced [16]. For operators, LTE unlicensed technologies' means synchronized integrated network management, the same authentication procedures, more efficient resource utilization, and thus lower operational costs. For wireless users, LTE unlicensed technologies' means enhanced user experience, i.e., higher data rates, seamless service continuity between licensed and unlicensed bands, ubiquitous mobility, and improved reliability. Thus, in the near future, dense deployments of LTE and Wi-Fi–based small cells are expected to coexist in shared spectrum.

The paper is organized as follows. In Section 2, we discuss types of LTE unlicensed technologies with deployment timeline. Section 3 describes the prospects for LTE/Wi-Fi coexistence with regard to operator or user concepts. Some challenges to coexistence are pointed out in Section 4. In Section 5, we elaborate possible mechanism for a solution. Finally, conclusions are drawn in Section 7.

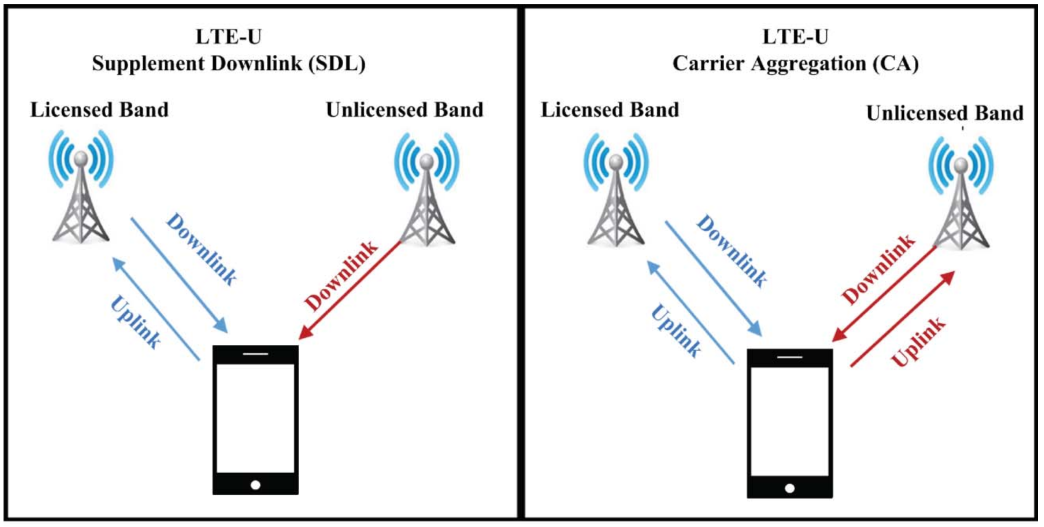
2. LTE IN UNLICENSED TECHNOLOGIES TYPES AND PLAN

Based on the aggregation of uplink/downlink in unlicensed spectrum, there are two types of LTE in unlicensed band, i.e., LTE-U/licensed assisted access (LAA) and standalone. LTE-U/LAA is an operational mode where unlicensed spectrum is always anchored with a licensed carrier to augment capacity.

Here, unlicensed spectrum is used only for the data plane, and all of the control plane is handled through the licensed spectrum. LAA can be further subdivided into two modes: Supplemental Downlink (SDL) mode and Carrier Aggregation (CA) mode. In SDL mode [16], as shown in Figure 2(a), unlicensed spectrum will only be used for the downlink, which enables significantly faster download and supports a much greater number of users with mobile devices. However, CA mode also named as extended LAA (eLAA) uses an unlicensed band for both uplink and downlink, as shown in Figure 2 (b), just like a typical LTE TDD system. Here, we have the flexibility to adjust the amount of resources between the uplink and downlink. LTE-U and LAA follows similar aggregation pattern for uplink and downlink but they have completely different operational parameters as shown in Table 2.

Next operational mode, standalone (SA) mode, supports both control-plane and data-plane traffic over unlicensed spectrum. It offers the possibility of higher spectrum efficiency and seamless mobility handling in interference-limited scenarios of LTE over unlicensed spectrum because it is a hallmark of LTE technology. However, this option has not been formally proposed by the 3GPP.

As of deployment plan, 3GPP plans to start over through duty cycle SDL for selected few countries. After that,



(a) Supplemental download link. (b) Carrier aggregation.

Figure 2: (a) Supplemental download link. (b) Carrier aggregation

Table 2: Difference between LTE-U and LAA

	LTE-U	LAA
Standardized	LTE-U Forum	3GPP RAN
Band support	2, 4 and 13 only (5150–5250 MHz and 5725–5850 MHz)	1, 2, 3, 4, 7, 41, and 42 band for anchor carrier (5150–5925 MHz)
CA support	Up to four unlicensed carriers	Up to two unlicensed carriers
Integration with licensed LTE	Supplemental Downlink (Carrier Aggregation in Uplink not needed)	Carrier Aggregation in UL and DL, using TDD
3GPP Release	Based on Release 10, 11 & 12	Based on Release 13
Co-existence with Wi-Fi	Dynamic Channel Selection CSAT based on LTE duty Cycle LBT support not needed	Dynamic Channel Selection LBT operation is mandatory
Regions supported	USA, Korea, China, India, etc.	Europe, Japan and beyond.
Commercialization	Early deployment possible	Will be commercialized later, due to ongoing standardization
Evolution path	No Plans	eLAA planned for REL-14

Embed of LBT (Listen Before Talk) feature in SDL and eLAA is planned for Release 13 and 14, respectively [17].

3. OPPORTUNITIES FOR LTE/WI-FI COEXISTENCE

LTE is considered to be a more established technology in the field of wireless communications. Implementing LTE in the unlicensed band brings benefits to the unlicensed band.

3.1 Higher Capacity, Better Coverage and Efficient Network Management

The coordinated and managed architecture of LTE in unlicensed spectrum offers better performance than Wi-Fi for the same transmit power. This improvement is derived from multiple aspects of LTE, such as (1) a more robust air link structure designed specifically for mobility, (2) best use of resources by managing and mitigating interference through coordination and synchronized architectures, (3) anchors in the licensed spectrum ensure control signaling is always efficiently delivered, and (4) a common set of signaling for both licensed and unlicensed spectrum reduces the overall overhead. Qualcomm [18] studies showed a two-fold, or more, increase in performance compared to Wi-Fi (i.e., one can get twice the capacity with the same amount of LTE nodes using unlicensed spectrum, compared to Wi-Fi).

The use of established LTE radio technology with existing radio network setup avoids developing new multiple solutions for network management. The operator can use the same existing acquisition, access, registration, security or authentication and mobility procedures. Moreover, having only a single technology simplifies the overall network maintenance, along with avoiding the need to upgrade any system elements.

3.2 Enhanced User Experience

In a wireless communication, higher throughput is desired for all network entities. CA technology [19] inbuilt in LTE Release 10 helps to aggregate both licensed bands and unlicensed bands, providing wider bandwidth that can be used to achieve higher throughput. Hence, users experience faster downloads and more responsive applications and services. Moreover, LTE in unlicensed technologies use the same LTE access methods in both spectrum (i.e., the same core network and the same integrated authentication), along with similar security and management strategies, resulting in seamless mobility. Therefore, users need not worry about selecting one or the other (or both) radios, or worse, experiencing interruption in the service. Also, the use of common integrated small cell will provide service on both bands. This ensures the maximization of performance in the unlicensed bands.

Licensed spectrums are highly reliable. The effort to use LTE in unlicensed bands can affect LTE embedded features, but the feature called "anchoring" helps to provide desirable performance even in an unreliable environment. Anchoring means that the important control message of LTE in unlicensed technologies is always transmitted through the licensed band, where QoS can be ensured.

3.3 Harmonious Coexistence with Incumbent Systems

Bringing LTE to unlicensed spectrum is an alternative option to Wi-Fi carriers. The first question asked is, "How will this affect existing Wi-Fi networks?" In light of this problem, LTE access to unlicensed band has been designed to harmoniously coexist with Wi-Fi, and in many cases, can be a better neighbor than Wi-Fi itself. Extreme care is being adopted during the development of LTE in unlicensed technologies to guarantee that Wi-Fi is protected and that LTE is a "good neighbor" in unlicensed bands (better neighbor than own system) [20]. Many approaches have been published for harmonious coexistence with incumbent systems, such as Duty cycled, LBT, Uplink power control, channel selection, etc., which will be discussed later in this paper.

3.4 Cost and Revenue

The capital expenditures (CAPEX) of LTE in unlicensed technologies deployment [21] can be kept at a reduced level for operators. All the existing backhaul, core network, and sites deployed for licensed LTE carriers can be reused, with updates only in eNodeBs (eNBs). From an operational perspective, a common RAN framework across the whole network allows unified operation and management between licensed and unlicensed spectrum, including operation, administration and management (OA&M) configuration, authorization, charging and RRM management. The efficient and convenient use of unlicensed spectrum would eventually lead to a better service experience. The user experience improvement and transparent use of unlicensed spectrum could provide operators more flexibility in charging strategies to get greater revenue from exploiting the unlicensed spectrum (compared to before).

4. CHALLENGES FOR LTE/WI-FI COEXISTENCE

To enable different networks to work in common shared spectrum, some issues need to be considered.

4.1 Reduced Wi-Fi Channel Access Opportunity

Almost all systems come with coordination and interference management between the same systems. It becomes especially challenging for heterogeneous systems to communicate with different time slots, scheduling modes, medium access modes, etc. Wi-Fi includes a carrier sense multiple access (CSMA) procedure to allow multiple Wi-Fi systems to coexist, while LTE does not implement any carrier sensing detection prior to transmission. LTE uses reserved channels for control and management, which makes concurrent transmissions possible. In addition, LTE also transmits periodic control and synchronization signals even when no traffic is delivered to devices. From this operational structure in both networks, Wi-Fi seems likely to be blocked by LTE transmissions in scenarios of coexistence, which could lead to performance degradation for Wi-Fi [22, 23]. Hence, LTE in unlicensed technologies are in need of fair coexistence solutions to equitably coexist with Wi-Fi. Additionally, the fair coexistence solutions should also consider increasing data rate efficiency, because coexistence techniques such as excessive clear channel assessment time for Wi-Fi, long back off periods for LTE, and overhead of media access control (MAC) layer signaling (designed to negotiate air frequency) may hamper data rate efficiency [24].

4.2 Regulatory Restrictions on LTE in Unlicensed Technologies Globalization

Regulatory frameworks for unlicensed bands across the globe appear to be different. In United States, China, and Korea, regulations governing the use of unlicensed spectrum primarily set strategies to protect adjacent-band and co-band primary users, with less stringent spectrum-sharing requirements among unlicensed users. However, in Europe, Japan, and India, the regulatory framework is not the same, and specific coexistence protocols are mandated in unlicensed spectrum, such as "listen before talk." So, these divergent regional regulatory requirements are likely to impact rollout of LTE in unlicensed technologies on a truly global scale [14]. Another challenge is with regulatory restrictions [25] on the deployment of LTE on unlicensed bands. The first limiting factor is effective isotropic radiated power (EIRP) in unlicensed spectrum bands, which restricts the radiating power of LTE to a much lower level than typically used in LTE macro cells [26]. A second limiting factor is that LTE must be capable to determine the existence of Wi-Fi in the same spectrum and able to differentiate whether Wi-Fi is jointly operating in the same spectrum, or establish a coexistence mechanism with it (internetworking). For this reason, LTE small cells tend to be a natural deployment model for LTE operation in unlicensed spectrum.

4.3 Tragedy of Commons

In unlicensed bands, the same portion of the spectrum is shared by different operators, such as Wi-Fi, Bluetooth, radar, etc. All operators have equal priority to access the same portion of the spectrum. More importantly, every LTE in unlicensed technologies' operator has an incentive to make the maximum use of the spectrum since it is freely available. In this case, independent and rational behavior exhibits by different operator to allocate the unlicensed spectrum for its use can risk LTE and Wi-Fi ecosystem causing tragedy of the commons. Uncoordinated resource management may find two operators choosing overlapped frequency bands and may deplete efficient use of that spectrum, making LTE in unlicensed technologies resource management more complicated and challenging. Additionally, lack of joint network planning may result in geographic overlap, or even closely located LTE in unlicensed technologies' cells, and severe cross-site chaotic inter-operator interference [21].

4.4 Tradeoff Between QoS and User Capacity

Traffic offloading issues have been extensively studied in with Release 11 and beyond [27]. Co-channel heterogeneous networks and cellular/Wi-Fi interworking are two popular technologies in the traffic offloading history of LTE. In both technologies, resource management for users focuses on the same system, either the LTE system or the integrated interworking system, whereas traffic offloading in the LTE in unlicensed technologies context should take into consideration user activities from other independent unlicensed systems in order to protect their performance. For example, delay experience by user to access the channel is proportional to the number of active unlicensed user present in that area. In addition, if we embed LBT features within LTE in unlicensed technologies, their small cells may not be able to occupy the unlicensed spectrum for a certain period, even if it is urgently needed by their users. This additional access delay rigorously affects the LTE user during handoff process from macro to LTE in unlicensed technologies small cell [28]. Hence, the performance of LTE in unlicensed technologies in unlicensed bands can be severely affected by occupation of other systems in channel access activity. Thus, LTE in unlicensed technologies offer a tradeoff between QoS in user performance and user capacity.

4.5 Deployment Concerns

Legacy coexistence mechanisms in Wi-Fi have been considered sufficiently in the wireless industry, and are currently in use by billions of Wi-Fi devices across the world. LTE in unlicensed technologies are new member of the unlicensed band, where Wi-Fi and other technologies currently coexist successfully. LTE in unlicensed technologies need to be designed in consideration of existing technologies. Since it is working with small cells, we obviously need a lot of small cells that can be deployed easily and anywhere, like a Wi-Fi access point (AP). In this regard, the challenge is not only confined to handling interference with existing Wi-Fi APs and interference with other small cells installed nearby [29]. There are lots of other concerns.

(1) Who is going to configure/optimize those small cells?
(2) Would it be an easy install, like a Wi-Fi AP (almost plug and play)? Or would it require special configuration/optimization for each installation?
(3) If we need to configure all those installed small cells one by one, who will do it? Installation engineers from the carrier?
(4) Can it be automated by a self-organizing network (SON)? Is SON mature enough to do this?

5. TECHNIQUES AND RESEARCH TREND FOR LTE/WI-FI COEXISTENCE

The difference in channel access strategies makes the channel blocking probability higher for Wi-Fi than LTE [22]. We need some techniques to limit LTE from accessing the channel for a long duration. The simple way to solve this issue is to share the spectrum for equivalent portions of time or a bandwidth. However, it does not necessarily provide each device in the network fair coexistence, which depends on a number of factors such as power, time, frequency, etc. Therefore, in the following section we review coexistence techniques.

5.1 Duty Cycling-Based Coexistence Technique

Certain region, such as Europe and Japan, prohibits continuous transmission and impose limits on the maximum duration of a transmission burst in unlicensed spectrum [14]. Hence, discontinuous transmission with limited maximum transmission duration is required functionality for LTE in unlicensed technologies. As a solution to the problem, LTE-duty cycle is proposed [30,31] in which LTE in unlicensed technologies periodically activate and de-activate using LTE MAC control elements. During the LTE in unlicensed technologies off period, the channel is available to nearby Wi-Fi which can resume normal Wi-Fi transmissions.

Most efficient way of duty cycling in LTE is via the Almost Blank Subframes (ABS) [31,32] defined in 3GPP Release 10. Figure 3 portrays ABS configuration. ABS consists of reserving a group of LTE subframes C, during which the macro nodes are partially muted (data, control, or reference symbols) allowing the users in pico eNBs to be served with lower interference. The LTE

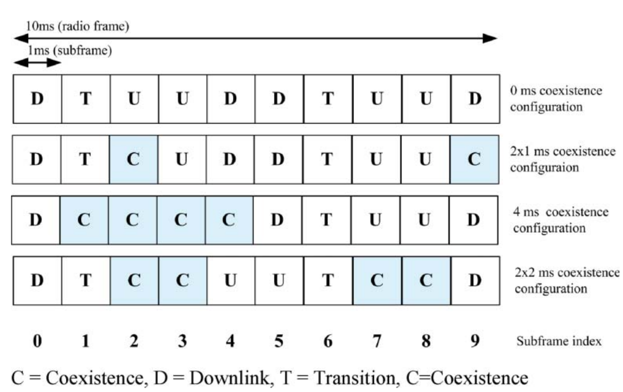


Figure 3: Blank subframe allocation

Table 3: Related research on duty cycling-based coexistence technique

Paper	Approach	Limitation	Scenario	Transmission
Almeida et al. [32]	Reuse of Almost Blank Subframe of LTE.	Loss of time resources and suffer interference from Wi-Fi nodes, which are not able to confine their transmission within the time ceded for coexistence.	Indoor	Downlink
Cano et al. [33]	Dynamically adapting suitable probability to access the channel.	Fail to allocate collision-free slot for LTE-U when multiple LTE-U networks from different operators.	Simple	Downlink
Rupasinghe et al. [24]	LTE TDD configuration with various numbers of uplink and downlink frame.	More numbers of downlink frame are expected than uplink in any Network. More numbers of uplink slot can effect LTE transmission.	Indoor/ Outdoor	Uplink/ Downlink
Choi et al. [30]	Control the time ratio between LAA and Wi-Fi through utility function.	Need data rate and load calculation of other operator can cause privacy issue.	Simple	Downlink
Xing et al. [31]	Predefined subframe muting configuration based on Wi-Fi load.	Does not consider about load and Qos of LTE.	Indoor	Downlink

silence period during these gaps provides the Wi-Fi system with an opportunity to access the channel. Wi-Fi uses these gaps for transmission, and it has to terminate connection, whenever LTE resumes communications. Nevertheless, we can see reusing the blank subframes ceded by LTE, and Wi-Fi throughput increases with the number of null-subframes. Different patterns of allocating muting subframes over a frame or an even longer time scale can be seen [31].

One apparent advantage of the successive pattern over the alternating one is that the active LTE subframes (statistically) less frequently intervene between ongoing WLAN transmissions. However, the long successive muting will induce larger delay jitter, which makes it inappropriate for real-time service. Hence, a tradeoff is established. Moreover, more degradation in LTE throughput is expected if blank subframes are nonadjacent, since Wi-Fi transmissions are not completely confined within LTE silent periods. Thus, a well-organized muting pattern with detection of LTE in unlicensed technologies signal or time/frequency synchronization of user equipment's (UEs) are desired. Table 3 shows some current research trends and their limitations on discontinuous data transmission.

5.2 Sensing-Based Coexistence Technique

One alternative solution for enabling coexistence is to follow a Wi-Fi-like carrier sensing model under LTE in unlicensed technologies [34] as shown in Figure 4. LTE in unlicensed technologies incorporates clear channel assessment [35, 36] functionality with the necessary politeness to fairly share the spectrum with Wi-Fi. The operation requires LTE in unlicensed technologies to listen to determine if the selected channel is idle for a contention period prior to any transmission (either inter- or intra-technology). Carrier sensing is mainly carried through energy detection (–82 dBm for Wi-Fi) rather than Wi-Fi preamble decoding .When LTE in unlicensed technologies detect certain channel availability, it must continuously sense it throughout this period to determine whether the channel continues to be available. LTE unlicensed technology then releases the channel for a specific back-off period before starting the process again. During these back-off gaps, Wi-Fi gets an opportunity to transmit. An appropriate value for contention window (CW) size and a CCA threshold for detecting WLAN activity allow us to ensure air time fairness with Wi-Fi. However, employing carrier sensing in LTE in unlicensed technologies results in a loss of many of the benefits from its continuous scheduling nature, and may not provide a fully functional system [35]. Therefore, efficiency of LTE in unlicensed technologies could approach that of Wi-Fi as a Wi-Fi-like coexistence procedure is applied to LTE in unlicensed technologies.

Hence, LTE in unlicensed technologies need to adopt a more adaptable mechanism that can be approved globally. Table 4 shows the existing research approaches and their shortcoming for sensing-based coexistence.

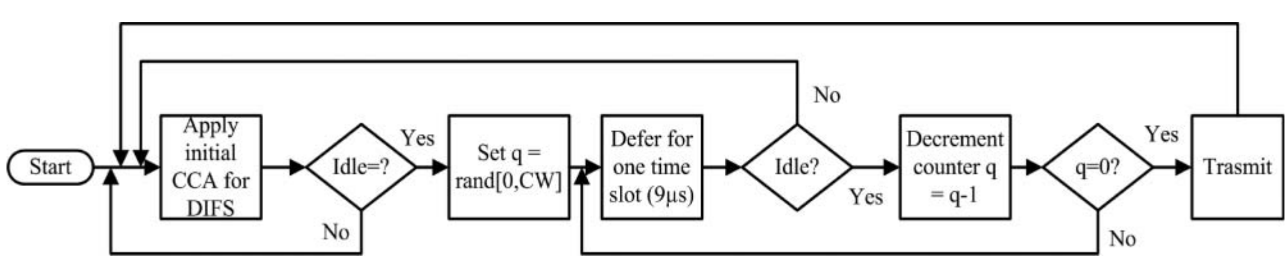


Figure 4: Conceptual flow diagram of Wi-Fi sensing mechanism

Table 4: Related research on sensing-based coexistence technique

Paper	Approach	Limitation	Scenario	Transmission
Li et al. [37]	Use upper bound and lower bound concept for dynamically adjusting the LAA CCA threshold and frequency reuse.	Upper bound and lower bound concept is limited to 802.11. It does not consider radar, Bluetooth, etc. Frequency reuse techniques are not explained.	Indoor/ outdoor	Downlink
Bhorkar et al. [34]	New LBT MAC protocol with channel reservation packets. Link adaptation algorithms are adopted to cope with collisions.	Reservation packets add overhead in communication.	Simple	Downlink
Jeon et al. [35]	Self-clear to send (CTS). RTS/CTS to set NAV of neighboring WLANs.	eNb must be equipped with WLAN transceiver to decode WLAN RTS/CTS message.	Indoor/ outdoor	Uplink/ downlink
Tao et al. [38]	Adaptive CW size adjustment based on QoS metric.	CW adjustment can result unnecessary collisions and retransmissions when the number of active stations changes sharply.	Indoor/ outdoor	Downlink
Jia et al. [39]	Periodic sensing and Persistent sensing.	Not good for delay sensitive application. Not energy-efficient in case of persistent sensing.	Indoor/ outdoor	Downlink

From the IEEE 802 interim meeting [14], LBT has become mandatory for 3GPP LAA. Various category LBT scheme is proposed. 3GPP Category 4 LBT scheme with random back-off with variable size CW is chosen to be the best for friendly and fair coexistence (see Figure 5). In this scheme, LBT procedure starts with CCA of 20 µs prior to a new transmission. If it finds the channel to be clear, it transmits immediately. On the other hand, if the medium is sensed to be busy, the transmission is deferred and an extended CCA (ECCA) is performed until the channel is idle. In an ECCA, the occupied channel is observed for the interval of a random factor "q" multiplied by the CCA observation time. "q" is the number of clear idle slots and the value is randomly selected between [1, q] every time an ECCA gets executed. The value of q is selected by the manufacturer in the range of [4, 32] based on the priority of the communication. The counter is decremented every time a CCA slot tends to be unoccupied. When the counter reaches zero, the equipment transmits.

5.3 Transmission Power Control-Based Coexistence Technique

Conventional LTE UE is facilitated with uplink (UL) power control technology [40] to improve capacity through fractional path loss compensation. The UE sets transmitting power using parameters and measures obtained from signals sent by the base station. LTE UL power control compensates for path loss. Subsequently, for UE experiencing high path loss, usually in the cell edge, compensation is done by allowing users to transmit with more power. Thus, this mechanism can create high interference with neighboring nodes, creating less opportunity for Wi-Fi users to detect a vacant channel. Hence, the conventional method of LTE power control based on path loss is not appropriate when considering Wi-Fi coexistence. In this case, interference with the neighboring cells must be taken into account.

Enhanced LTE UL power control proposed in [41] emerges as a flexible and easily implementable solution to deal with the trade-off between LTE and Wi-Fi performance in heterogeneous environments. Here, they improve LTE UL power control with an interference-aware power operating point with a controlled level of penalization on transmit power. The interference measurements employed at LTE eNBs and/or UE allow estimation of the presence and proximity of Wi-Fi nodes. UE measuring high interference is more likely to cause high interference, so additional power control factors are introduced to decrease the transmit power of LTE UE. Path loss and interference are compensated for given signal-to-interference-plus-noise ratio (SINR) at the

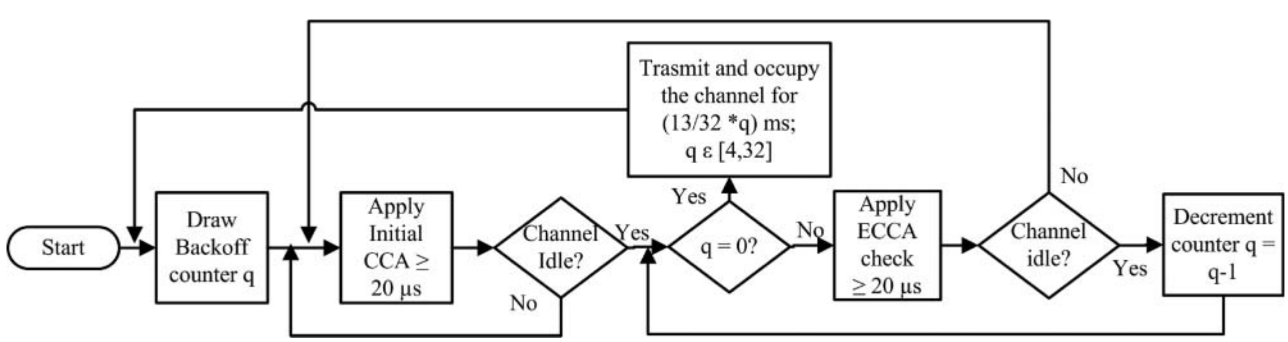


Figure 5: Conceptual flow diagram of LTE sensing mechanism

Table 5: Related research on transmission power-based control coexistence technique

Paper	Approach	Limitation	Scenario	Transmission
Xia et al. [42]	Studies the interaction of optimal transmit power and Clear Channel Assessment.	Scenario dependent (room dimension, penetration loss, etc.) are not consider.	Indoor	Uplink
Chaves et al. [41]	Interference aware penalization on the transmit power.	Delay for LTE user and may need retransmission to meet Qos.	Indoor	Uplink/ downlink
Lieu et al. [43]	Optimize transmit power for traffic balancing.	Only FDD mode for LTE. Latency experience by user was not explained.	Outdoor	Uplink/ downlink
Teng et al. [44]	Transmit power spectral density for spectrum sharing mechanism.	Operators are not always rational for utility. Priority of message.	Simple	Not mentioned
Xu et al. [45]	Co-channel interference management through allocation of transmit power.	Does not consider other users in unlicensed band.	Simple	Uplink/ downlink

LTE eNB receiver. Consequently, it gives an opportunity for Wi-Fi transmissions when Wi-Fi nodes detect the channel as vacant. Hence, this technique effectively reduces LTE/Wi-Fi intercellular interference and provides a fair LTE/Wi-Fi coexistence scenario. Similarly, as shown in Table 5 various other approaches are proposed based on transmit power for interference free LTE/Wi-Fi Coexistence.

5.4 Channel Selection-Based Coexistence Technique

LTE is built to be used in licensed spectrum with planned deployment, whereas Wi-Fi is equipped for unlicensed bands with uncoordinated deployment. Both technologies have different channel allocation technologies and network deployment. Therefore, when we think about the coexistence of both technologies sharing the same frequency bands, LTE dominates the coexistence with Wi-Fi [23]. For that reason, most of the time, the channel is blocked to Wi-Fi. Therefore, enabling the cleanest channel selection based on LTE and Wi-Fi coordination seems to be an important enabler for LTE/Wi-Fi coexistence. The uncoordinated nature of Wi-Fi deployment and the limitation of non-overlapping channels in the Industrial, Scientific, and Medical (ISM) bands have inspired several studies about channel selection for Wi-Fi networks. Table 6 shows various research and limitation of Channel selection mechanism, such as least congested channel search (LCCS) [46], which could also be exploited in coexistence with LTE. An innovative work by Qualcomm [47] presents a simple yet effective policy for dynamic channel selection. Here, they measure the interference and use it to switch between channels if interference exceeds a predefined threshold. With the assistance of UE feedback information, measurement accuracy is significantly improved and the hidden terminal problem is effectively avoided. Alternatively, subcarrier allocation flexibility provided by orthogonal frequency-division multiplexing (OFDM) and orthogonal frequency-division multiple access (OFDMA) [48] techniques can also be exploited in coexistence scenarios. Instead of fixed bandwidth channels, adaptive bandwidth channels could be defined and selected in coexistence scenarios [23]. However, there exists an issue where exchange of information between nodes experiencing interference relies on a common inter-technology communications framework, which is currently unavailable for LTE and Wi-Fi.

5.5 Co-Operative Coexistence Technique

So far we have discussed about non-cooperative technique where there is no exchange of messages among coexisting systems. In contrast, cooperative mechanisms require mutual agreement on parameters used by each network, and include minimal change in the existing air interface technology. In recent months, there is intensive research (see Table 7) in cooperative mechanisms [23, 26, 32] due to greater potential to deliver better performance for all coexisting networks, rather than on non-cooperative mechanisms. For cooperative mechanisms, different procedures are followed [26].

Dulaimi et al. [26] propose centralized cooperative control management that employs network function virtualization (NFV), which enables seamless transfer of

Table 6: Related research on channel selection-based coexistence technique

Paper	Approach	Limitation	Scenario	Transmission
Qualcomm [47]	Cleanest channel based on Wi-Fi and LTE interference measurements.	Need inter- technology communication	Outdoor	Downlink
Abinader et al. [46]	Least congested channel search.	Must use static channel setting and dynamic channel setting can cause overhead.	Indoor/ Outdoor	Uplink/ downlink
Nihtila et al. [23]	Bandwidth sharing mechanism	Continuously monitor the Wi-Fi channel.	Indoor	Downlink
Al-Dulaimi et al. [26]	Frequent switching of channel to allow Wi-Fi to access.	Loss of packet and retransmission. Channel utilization loss.	Simple	Uplink/ downlink
Song et al. [49]	Exchange of status information of frequency band for interference cancellation.	Security issues.	Outdoor	Downlink

Table 7: Related research on cooperative-based coexistence technique

Paper	Approach	Limitation	Scenario	Transmission
Dulaimi et al. [26]	Centralized cooperative control management using network function virtualization	Chances if single point of failure	Simple	Uplink/ downlink
Almeida et al. [32]	LTE time domain collaborative	LTE throughput decreases both for losing time resources and from suffering interference from Wi-Fi.	Indoor	Uplink/ downlink

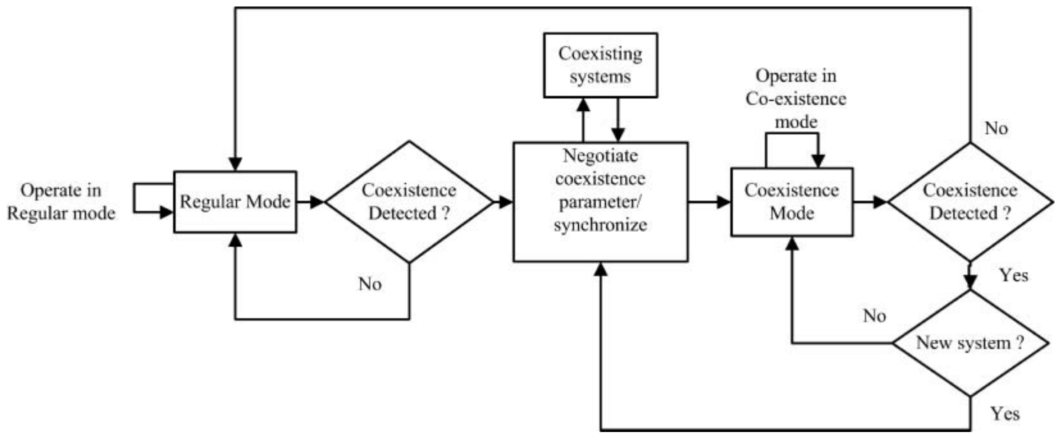


Figure 6: Conceptual flow diagram of cooperative coexistence

resources between LTE in unlicensed technologies and Wi-Fi using in-the-cloud control of the distributed access point. Likewise, other researchers [24, 32] proposed algorithms where both networks exchange messages to negotiate a coexistence mode. In the procedure, each technology has operation modes: regular mode and coexistence mode. Figure 6 depicts the generalized cooperative coexistence algorithm. In regular mode, they assume that no other technology is accessing the spectrum at that location. The system scans for coexisting systems periodically when it is triggered by an external event, such as a change in the received interference or detection of a beacon. If a coexisting system is detected, then the system goes through a negotiation phase shortly after the identification of, and synchronization with, the identified system. In the negotiation phase, all systems that are sharing this spectrum band negotiate parameters for fair coexistence. After the negotiation phase, each system reconfigures parameters accordingly, to ease operation for the other system. This parameter modification is referred as coexistence mode. Coexistence mode is followed by monitoring of the shared resource in order to check whether the channel is being effectively used or not. If the resource is still used, the system continues in coexistence mode; if not, the system returns to regular mode. Moreover, there is a probability for the appearance of new users while in coexistence mode; hence, the system must also perform regular scans for new users and return to the negotiation phase as needed, which was not explained in [32].

Although various coexistence techniques [26–49] have been proposed for fair coexistence between LTE/Wi-Fi coexistence. But, it still does not clearly specify a fair spectrum access in terms of time and bandwidth. Fairness criteria must include equal access to the unlicensed band in terms of air time as well as spectrum allocations. In addition to the throughput and delay, performance metrics for evaluation of coexistence behavior should also include jitter, packet loss, frame retransmission rate, beacon loss, and power save signaling loss which has not been mentioned in any of the research technique. Furthermore, demand-based fair share between operators is expected and is future research challenge for all LTE in unlicensed technologies researchers.

6. CONCLUSION

Growing traffic demand and the significant amount of underutilized spectrum in the Wi-Fi band are motivating operators to combine LTE with Wi-Fi technologies. In this paper, we provide an overview of LTE in unlicensed bands as a seamless approach to enable traffic offload. Compared to Wi-Fi, LTE unlicensed technologies promise higher throughput and spectral efficiency, with estimates ranging from two-fold or more improvements over Wi-Fi. We also discuss two possible deployment modes: (1) unlicensed spectrum aggregated with existing licensed channels, and (2) unlicensed spectrum acting as the only carrier for LTE in unlicensed technologies, where both data and control channels reside. New LTE in unlicensed technologies coexistence challenges with existing possible solutions for other technologies operating in the unlicensed bands, particularly for legacy Wi-Fi is also explained. Lastly, two different existing algorithms, non-coordinated and coordinated coexistence with modification for better performance, have been shown. Future research is required to find a more sophisticated coexistence mechanism that can ensure higher LTE performance when it coexists with Wi-Fi, ensuring significant Wi-Fi performance.

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