Coexistence of LTE-LAA and Wi-Fi on 5 GHz With Corresponding Deployment Scenarios: A Survey

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***Abstract*—Long term evolution (LTE) carrier aggregation with 5 GHz unlicensed national informational infrastructure band has been pointed out by the industry as a good solution to handle the rapidly increasing amounts of data traffic. To provide fair coexistence of LTE-licensed assisted access (LTE-LAA) and Wi-Fi on 5 GHz, several coexistence mechanisms have already been proposed. This paper provides a comprehensive survey of the coexistence of LTE-LAA and Wi-Fi on 5 GHz with corresponding deployment scenarios. We first analyze coexistence-related features of those two technologies, including motivation, LTE carrier aggregation with unlicensed band, LTE and Wi-Fi medium access control protocols comparison, coexistence challenges and enablers, performance difference between LTE-LAA and Wi-Fi, as well as co-channel interference. Second, we further extensively discuss current considerations about the coexistence of LTE-LAA and Wi-Fi. Third, influential factors for the classification of small cell scenarios, as well as four representative scenarios are investigated in detail. Then we explore a relatively smooth technical route for solving coexistence-related problems, which practically takes features of a specific scenario as the base for designing deployment mode of LTE-LAA and/or Wi-Fi. A scenario-oriented decision making procedure for the coexistence issue and the analysis on an example deployment scenario, including design and performance evaluation metrics focusing on the concept of the scenario-oriented coexistence are presented. We finally forecast further research trends on the basis of our conclusion.**

***Index Terms*—Scenarios-oriented, coexistence, LTE-LAA, Wi-Fi, 5 GHz UNII spectrum.**

I. INTRODUCTION

AS THE rapid progress and pleasant experience of Internet-based services, there is an increasing demand for high data rate in wireless communications systems such that the growth of mobile traffic in the next decade is over one thousand times [1]. However, since the usable licensed spectrum is of limited physical extent, new licensed frequency bands are becoming rare and expensive. To respond to increased wireless communication capacity demand, the innovation focusing on such techniques that enable better use of different types of spectrum for traffic offload, including unlicensed bands, is urgently needed [2]. It is assumed that up to thirty percent of broadband access in cellular networks can be offloaded to unlicensed bands, primarily Wi-Fi networks until now [3].

The extension of LTE-LAA over 5 GHz UNII band and the requirement to provide fair coexistence of LTE-LAA with other technologies working on 5 GHz are two major observations of the ongoing discussion on the 3rd Generation Partnership Project (3GPP) [4], [5]. While considering the coexistence of Wi-Fi and LTE-LAA in 5 GHz UNII spectrum, designers should ensure that LTE-LAA can coexist with Wi-Fi fairly and friendly in unlicensed band by complying with regulatory requirements of the local government in a region. In some markets, like the U.S., South Korea and China, there is no Listen-Before-Talk (LBT) requirement. Without changing LTE air interface protocol, coexistence with Wi-Fi in those scenarios can be realized for LTE Release 10-12 by using specific techniques such as Carrier Sense Adaptive Transmission (CSAT). In markets like Europe and Japan where LBT is required, however, LTE air interface would need changes with the introduction of LBT feature potentially in 3GPP Release 13 [6].

To the best of our knowledge, current research mainly aims at such mechanisms as capable of enabling the coexistence of LTE-LAA and Wi-Fi. It should be noticed that the coexistence performance of LTE-LAA and Wi-Fi in 5 GHz UNII spectrum would vary a lot in different deployment scenarios. Take the early coexistence results in [7] and [8] for example, the ratio of the downlink (DL) throughput gain of LTE-LAA to that of Wi-Fi would be different if the simulation scenario changes from outdoor to indoor. The throughput also differs when an operator chooses to place Picocells uniformly or in a hotspot region [6]. Both LTE-LAA and Wi-Fi have their own benefits and cannot be replaced by each other at the moment [9]. The performance of either LTE-LAA or Wi-Fi should be maintained and not be affected by each other while deployed in 5 GHz spectrum together.

Focusing on those important issues, this paper surveys the coexistence of LTE-LAA and Wi-Fi on 5 GHz with corresponding deployment scenarios, and introduces a scenario-oriented decision-making method for coexistence. The rest of the paper is organized in the following manner. In Section II, we provide a comparative study of existing LTE surveys and this paper. In Section III, relevant features of Wi-Fi and LTE-LAA are overviewed. In Section IV, we first overview the coexistence mechanisms related researches. Then we review the LTE-LAA and Wi-Fi coexistence testing and results to present a picture of the research stage in the community.

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We also investigate the current coexistence mechanisms in both markets where LBT is required or not, so as to evaluate their influence on wireless service. In addition, we also provide lessons learnt from different coexistence mechanisms comparison and Cognitive Radio (CR), as well as propose recommendations and guidelines for ensuring fairness. In Section V, we analyze eight key influential factors for the classification of SC scenarios, demonstrate several representative scenarios, and dissect an example of deployment scenario to highlight the concept of the scenario-oriented coexistence for different access applications. We further recommend performance evaluation scenarios and metrics. In Section VI, we discuss future research trends. Finally, we conclude in Section VII. For convenience, please refer to the Table I for all acronyms in the paper.

II. Comparative Study of Existing Surveys on LTE and This Paper

In order to provide a broader perspective, as well as to give directions to readers about the key distributions of this survey, we illustrate a comparative study of the existing surveys on LTE and this paper.

Here we investigate several representative surveys reviewing the LTE-related technologies from different aspects. Authors in [10] first review the evolution of LTE physical (PHY) layer control channels. Moreover, in [11]–[13], authors focus on radio resource management (RRM) for LTE and LTE Advanced (LTE-A) from different angles. To be more specific, authors in [11] demonstrate Heterogeneous Networks (HetNets), particularly on femto cells and relay nodes. In [13], authors study RRM for spectrum aggregation. Resource allocation and link adaptation are overviewed in [12]. What's more, in [14]–[19], authors review the Uplink (UL) or Downlink (DL) scheduling from different angles. In particular, authors in [14] classify LTE UL scheduling from the perspective of Machine-to-machine (M2M) communications. In [15], authors demonstrate cooperative UL transmissions beyond LTE-A system. In [16], authors summary UL scheduling in LTE and LTE-A. Authors in [18] demonstrate DL packet scheduling in LTE cellular network. Multi-cell coordinated scheduling, particularly inter-cell interference mitigation techniques for DL and UL are reviewed in [17]. As a supplement to [17], multi-cell scheduling strategies in LTE and LTE-A are also overviewed in [19]. In addition, there are also some surveys discussing corresponding techniques enabling communications in LTE networks. In [20], authors review M2M communications in the context of LTE and LTE-A. Authors in [21] review Device-to-Device communications in LTE networks. Security aspects for LTE and LTE-A networks are overviewed in [22]. In [23], authors also review the mobility management support in LTE-A networks. Authors discuss alternatives to improve the operation of the random access channel of LTE and LTE-A in [24].

Unlike these surveys which are targeted only for a single Radio Access Network (RAN), i.e., LTE, this paper focuses on the study of LTE-LAA and Wi-Fi coexistence in 5 GHz, including coexistence-related features, coexistence considerations, deployment scenarios for the coexistence and scenario-oriented decision making. Table II shows a brief summary of the related survey papers on LTE and this article.

TABLE I
Acronyms in the Paper

Acronym	Definition/explanation
3GPP	3rd Generation Partnership Project
ABS	Almost Blank Subframe
ACK	Acknowledgement Packet
AP	Access Point
BS	Base Station
CBD	Central Business District
CCA	Clear Channel Assessment
CCU	Cell Center User
CEU	Cell Edge User
CHS	Channel Selection
CoMP	Coordianated Multi-point
CQI	Channel Quality Indicator
CR	Cognitive Radio
CRS	Cell-specific Reference Signal
CSAT	Carrier Sense Adaptive Transmission
CSMA/CA	Carrier Sense Multiple Accesses Collision Avoidance
CTS	Clear to Send
CUBS	Channel Usage Beacon Signals
DCF	Distributed Coordination Function
DL	Downlink
DTX	Discontinuous Transmission
eICIC	enhanced ICIC
eNB	evolved NodeB
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
GP	Guard Period
HARQ	Hybrid Automatic Repeat Request
HetNet	Heterogeneous Network
ICIC	Inter-cell Interference Coordination
LBT	Listen-Before-Talk
LOS	Line of Sight
LTE	Long Term Evolution
LTE-A	LTE Advanced
LTE-LAA	LTE-licensed Assisted Access
LTE-U	LTE-Unlicensed
LWA	LTE-WLAN Radio Level Aggregation
M2M	Machine-to-machine
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MSA	Multi-stream Aggregation
OFDM	Orthogonal Frequency Division Multiplexing
OSDL	Opportunistic SDL
PCell	Primary Cell
PDCCH	PHY DL Control Channel
PDSCH	PHY DL Shared Channel
PHY	Physical Layer
PPDU	Physical Protocol Data Unit
PSD	Power Spectral Density
PSS	Primary Synchronization Signal
PU	Primary User
PUCCH	PHY UL Control Channel
PUSCH	PHY UL Shared Channel
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio Frame
RRH	Remote Radio Head
RRM	Radio Resource Management
RS-CS	Resource Specific Cell Selection
RTS	Request to Send
SC	Small Cell
SCell	Secondary Cell
SDL	Supplemental DL
SINR	Signal to Interference plus Noise Ratio
SON	Self-organizing Network
SSS	Secondary Synchronization Signal
STA	station
SU	Secondary User
TDD	Time-Division-Duplexed
UE	User
UL	Uplink
UNII	Unlicensed National Informational Infrastructure
WLAN	Wireless Local Area Network

TABLE II
COMPARATIVE STUDY OF OUR WORK WITH EXISTING SURVEYS ON LTE

Item	Key word	Description
Our work	Coexistence	A comprehensive survey on LTE-LAA and Wi-Fi coexistence in 5 GHz 1. analysis on coexistence-related features of LTE-LAA and Wi-Fi; 2. current research on LTE-LAA and Wi-Fi coexistence considerations; 3. deployment scenarios for the coexistence and scenario-oriented decision-making; 4. challenges and further research directions.
[10]	PHY	The evolution of LTE PHY layer control channels: 1. an overview of the legacy LTE control channel and challenges; 2. the new solutions provided by LTE Release 11; 3. limitations of the new design.
[11]	RRM	RRM for LTE/LTE-A HetNets, particularly for femtocells and relay nodes: 1. key challenges from HetNet; 2. radio resource management schemes; 3. schemes classification and comparison according to approaches.
[12]	RRM	Resource allocation and link adaptation in LTE and LTE-A: 1. the units for resource allocation modes and purposes; 2. the way the resource allocations are encoded under these different modes; 3. methods of link adaption; 4. the control signaling encoding for link adaption; 5. the encoding of channel state feedback.
[13]	RRM	RRM for spectrum aggregation in LTE-A: 1. spectrum aggregation techniques; 2. radio resource management aspects and algorithms to support carrier aggregation; 3. technical challenges for future research on aggregation in LTE-A.
[14]	UL/DL scheduling	Classification of LTE UL scheduling techniques from the perspective of machine-to-machine communications: 1. power efficiency; 2. QoS support; 3. multi-hop connectivity; 4. scalability for massive number of users.
[15]	UL/DL scheduling	Cooperative UL transmissions of systems beyond the LTE-A initiative: 1. single-carrier Frequency Division Multiple Access (FDMA) and the localized FDMA comparison; 2. the philosophy of both user cooperation and cooperative single-carrier FDMA; 3. benefits of relying in LTE-A.
[16]	UL/DL scheduling	UL scheduling in LTE and LTE-A: 1. scheduling in LTE and LTE-A; 2. schemes that address the scheduling problem; 3. an evaluation methodology to be as a basis for comparison between scheduling.
[17]	UL/DL scheduling	Multi-cell coordinated scheduling and multiple-input multiple-output techniques in LTE: 1. single user multiple-input multiple-output; 2. multi user multiple-input multiple-output; 3. inter-cell interference mitigation techniques for DL and UL; 4. potential research challenges on physical limitation of user equipment, feed back consideration and enhanced codebook-based transmission.
[18]	UL/DL scheduling	DL packet scheduling in LTE cellular networks: 1. the design of a resource allocation algorithm for LTE networks; 2. a survey on the most recent techniques, including channel-unaware strategies, channel-aware/QoS-unaware strategies, channel-aware/QoS-aware strategies, semi-persistent scheduling for voice over Internet phone support and energy-aware strategies; 3. performance comparisons of the above well-known schemes.
[19]	UL/DL scheduling	Multi-cell scheduling strategies in LTE and LTE-A: the evolution of interference management.
[20]	Techniques enabling communications	Machine-to-machine communications in the context of the LTE and LTE-A: 1. architectural enhancements for providing machine-to-machine services; 2. the signal overheads and various QoS requirements in machine-to-machine communications; 3. application scenarios; 4. machine-to-machine challenges over LTE/LTE-A and issues on random access overhead control.
[21]	Techniques enabling communications	Device-to-Device communication in LTE networks: related research works ranging from technical papers to experimental prototypes to standard activities.
[22]	Techniques enabling communications	Security aspects for LTE and LTE-A networks: 1. an overview of the security aspects of the LTE and LTE-A networks; 2. the security vulnerabilities in the architecture; 3. the design of LTE and LTE-A networks; 4. the existing solutions to security problems.
[23]	Techniques enabling communications	Mobility management support in the presence of femtocells in LTE-A: 1. key aspects and research challenges of mobility management support 2. mobility management procedures in the LTE-A system; 3. handover decision algorithms
[24]	Techniques enabling communications	Alternatives to improve the operation of the random access channel of LTE and LTE-A: 1. discussion of the limits of LTE and LTE-A to handle M2M applications; 2. performance evaluation of the energy efficiency of the random access mechanism of LTE; 3. existing improvements of the random access channel, including optimized MAC, access class barring, separation of random access resources and distributed queuing for M2M applications.

III. ANALYSIS ON COEXISTENCE-RELATED FEATURES OF LTE-LAA AND WI-FI

For a better understanding of coexistence mechanisms between LTE-LAA and Wi-Fi, brief summaries of several coexistence-related features of the two technologies are reviewed in this section.

A. Motivation of Using LTE With Wi-Fi in 5 GHz

The current mobile networks are facing great capacity challenges. Benefits promised by the coexistence of Wi-Fi and LTE networks in unlicensed spectrum have started to attract interest from the research community [2]. For example, LTE-LAA causes less adjacent channel interference to a Wi-Fi system

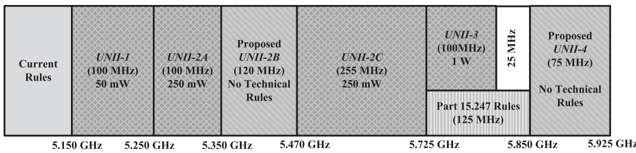

Fig. 1. 5 GHz unlicensed spectrum under consideration [28].

compared to another Wi-Fi system [25]. In other words, LTE-LAA is a better neighbour than another Wi-Fi system in terms of adjacent channel coexistence with a Wi-Fi system. On the other hand, as stated in [26] and [27], combined LTE and Wi-Fi can unquestionably increase the traffic load in the band, the contention for spectrum resources, and the congestion if the coexistence of LTE and Wi-Fi is not satisfactorily arranged.

To be clear, the reason to adopt LTE in 5 GHz is not to unseat Wi-Fi, but to increase the spectral efficiency and capacity of the 5 GHz band, and to do so with the technology that is fully integrated within the mobile operators networks. In fact, it is envisioned that Wi-Fi and LTE will exhibit complementary benefits that can be leveraged for an efficient integration. On the one hand, due to the uncontrolled nature of Wi-Fi, the competition for resources among a large number of hotspot users can yield dramatically poor throughputs. Offloading some of this traffic to the well-managed LTE network becomes necessary. On the other hand, due to cross-tier and co-tier interference among LTE networks, some of the traffic can also be offloaded from LTE networks to the Wi-Fi band, so as to alleviate the interference and ease congestion.

B. LTE Carrier Aggregation With Unlicensed Band

1) 5 GHz Unlicensed Spectrum Under Consideration: For the sake of clearer channel conditions, wider spectrum, and easier implementation, the unlicensed frequency band of common interest in 3GPP is the 5 GHz UNII band mainly used by IEEE 802.11-based Wireless Local Area Network (WLAN), or Wi-Fi currently [4].

With regard to the availability of 5 GHz spectrum, different countries have their regional requirements on 5 GHz UNII band in the form of regulations or rules. As shown in Fig. 1, the spectrum 5.15-5.35 GHz (UNII-1, UNII-2A) is available in the U.S., Europe, Japan and China. 5.47-5.725GHz (UNII-2C) is open for unlicensed wireless access for the U.S., Europe and Japan. In addition, 5.725-5.85 GHz (UNII-3) is available for the U.S., China, and being considered as new spectrum additions to extend unlicensed use in Europe. Furthermore, there are still 195 MHz bands (proposed UNII-2B 5.35-5.47 GHz and proposed UNII-4 5.85-5.925 GHz) that could be available in the U.S., Europe and China in the future [28].

2) LTE-LAA and LTE-U: It should be taken into account that the transmission relying only on unlicensed spectrum is unstable since the nature of being unlicensed makes it hard to provide guaranteed Quality of Service (QoS) [4]. Therefore, it seems unreasonable to ignore the usage of licensed spectrum during the extension of LTE spectrum access. To allow users to access both licensed and unlicensed spectrum and to study the use of unlicensed band under a unified LTE network infrastructure, LTE-LAA is initiated as part of 3GPP LTE Release 13 [29], [30]. According to the design, LTE-LAA in unlicensed spectrum is an extension of the LTE carrier aggregation protocol [31]–[34]. LTE-LAA on unlicensed band is always combined with licensed band LTE and is replacing the current terminology of LTE-U [4], which is a natural extension of LTE carrier aggregation to unlicensed band as a part of secondary carriers. Besides using unlicensed spectrum targeting at 5 GHz UNII band at present, LTE-LAA tends to include every kind of technology that would augment licensed spectrum operation [35].

As it requires fewer modifications from licensed LTE compared to LTE-LAA, LTE-U will be the first version of LTE unlicensed to be available in commercial deployments. However, because it does not implement LBT mechanisms, LTE-U can only be used in markets where regulation does not require LBT, such as China, South Korea, India and the USA. LTE-LAA, on the other hand, is the version of LTE in unlicensed band that 3GPP standardizes in Release 13. It supports LBT in addition to carrier aggregation. LTE-LAA is set to become a global standard as it strives to meet regulatory requirements worldwide. Nevertheless, because the standardization work had not been completed until March 2016, commercialization will take longer than for LTE-U. For details referring to the LBT mechanisms, see Section III-D. For more details about LTE carrier aggregation, refer to [10]–[12], [20], and [24].

3) Integration of LTE Licensed and LTE Unlicensed: As stated above, if there is additional capacity demand, to manage the different component carriers, carrier aggregation may be employed with one carrier serving as the Primary Cell (PCell) and others serving as Secondary Cells (SCells) [36], [37]. The unlicensed spectrum may be employed by cellular systems in different ways, distinguished by the supplementary and control channel configurations shown in Fig. 2. In some systems, the aggregation is based on what is supported in 3GPP Release 12 [38]. In this case, the second carrier would be a Time-Division-Duplexed (TDD) carrier or Supplemental DL (SDL) only. In the SDL mode, the unlicensed band is used to carry data traffic originally staying in the licensed spectrum, while the UL and control channel remain in the licensed spectrum. In the TDD carrier aggregation mode, the unlicensed band is capable of carrying data traffic in both UL and DL directions while the control channel remains in the licensed spectrum. In other systems, the unlicensed spectrum may be employed in a standalone configuration, with all carriers operating in the unlicensed spectrum exclusively. A representative LTE-based technology for unlicensed spectrum without licensed anchor channel is called MuLTEfire alliance, which is formed by Nokia and Qualcomm [39]. It is a solution that may be attractive to cable operators, wireless Internet service providers or hotspot network operators who lack licensed spectrum. This mode has not been discussed in 3GPP yet.

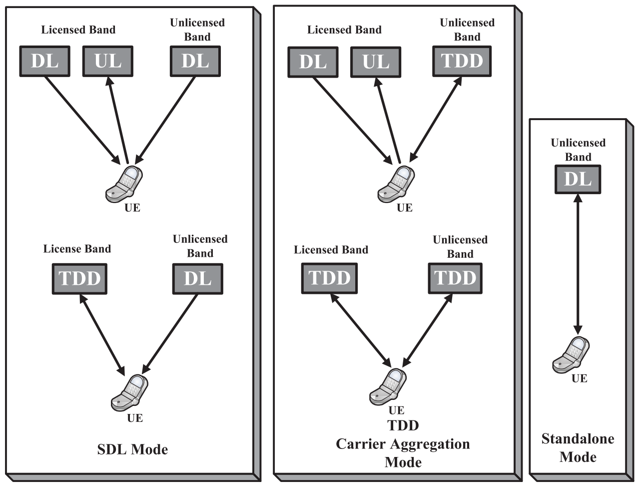

Fig. 2. Integration of LTE licensed and LTE unlicensed. UE refers to user.

C. LTE and Wi-Fi MAC Protocols

In this part, we briefly review the load-based Wi-Fi and frame-based LTE MAC layers.

1) LTE MAC Protocol: The key enabling technology of LTE systems is orthogonal frequency division multiple access. For better QoS control, transmission spectral efficiency and inter-cell coordination, transmission in LTE has to follow a continuous stream of a deterministic frame structure, i.e., a Radio Frame (RF). An LTE RF consists of ten 1 ms subframes, each one is further divided into two 0.5 ms slots [10], [11], [14], [21]. For further details about LTE frame structure, refer to [12], [15], [16], [20], and [40].

The LTE system adopts a centralized MAC protocol, which includes a dynamic resource scheduler that allocates physical resources on PHY DL Shared Channel (PDSCH) for data traffic. The scheduler takes into account the traffic volume, the QoS requirement, and the radio channel conditions when sharing the physical resources among mobile devices. For DL data transmissions, the evolved NodeBs (eNBs) transmits the PDSCH resource assignments and their Modulation and Coding Scheme (MCS), on PHY DL Control Channel (PDCCH), and the data packet on the PDSCH accordingly. The mobile device needs to monitor its PDCCH in the control region to discover its grant. Once its PDCCH is detected, the mobile device decodes PDSCH on allocated resources using the MCS provided. For more details about LTE MAC protocol and radio resource management, refer to [11], [13], and [14].

2) Wi-Fi MAC Protocol: A Wi-Fi node, on the contrary, with no need for centralized controller, will first sense the channel whenever it has a pending transmission. The MAC layer of Wi-Fi is based on the Carrier Sense Multiple Accesses with Collision Avoidance (CSMA/CA) mechanism [41], so Wi-Fi systems do not require a centralized controller as is needed in LTE systems [42]. The basic idea of CSMA/CA is to sense the channel to determine whether the wireless medium is busy or not. Only if the channel is sensed to be not busy, or idle, is a Wi-Fi station (STA) permitted to transmit. The CSMA/CA mechanism particularly used in the IEEE 802.11 MAC is also known as the Distributed Coordination Function (DCF), which enables multiple Wi-Fi STAs to access the channel according to the order they start sensing the channel [43], [44].

DCF is very effective when the medium is not heavily loaded, since it allows STAs to transmit with minimum delay. However, there is always a chance of collision, i.e., several STAs transmitting at the same time, due to the fact that these STAs sense the medium free and decide to transmit at once. In order to overcome this problem, Wi-Fi uses a collision avoidance mechanism. As a matter of fact, if the medium is free for a specified time, defined as distributed inter frame space, the STA is then allowed to transmit, the receiving STA will check the cyclic redundancy check of the received packet and send an Acknowledgement Packet (ACK). Receipt of the ACK means that no collision occurred. Besides the above mechanism, IEEE 802.11 Wi-Fi standard also defines a virtual carrier sense mechanism. When an STA is willing to transmit a packet, it will first transmit a short control packet called Request to Send (RTS). As a response to the RTS, the destination STA will send a Clear to Send (CTS) back. All STAs receiving RTS/CTS will set their virtual carrier sense indicator, and will use this information together with the physical carrier sense when sensing the medium. For more details about DCF and related collision avoidance mechanisms, refer to [41].

The fundamental difference between LTE and Wi-Fi MAC layers has caused some issues on the coexistence of the two systems [45]. We will focus on coexistence challenges and enablers as well as the choice of LTE-LAA and Wi-Fi in Sections III-D and III-E respectively.

D. Coexistence Challenges and Enablers

The main challenge for the coexistence of LTE-LAA and Wi-Fi is while operating LTE-LAA in the presence of Wi-Fi making use of the same band, the performance of Wi-Fi systems will be significantly affected, while the performance of LTE is nearly unchanged since Wi-Fi moves to silence mode due to the CSMA/CA mechanism. That is due to the fact that these two technologies use different channel usage and access procedures. LTE is designed based on the assumption that one operator has exclusive control of a given spectrum. It will continuously transmit with minimum time gap even in the absence of data traffic. LTE also has an almost continuously transmitting protocol, as well as a periodically transmitting protocol to transfer a variety of control and reference signals. Wi-Fi, on the contrary, is designed to coexist with other technologies through random backoff and channel sensing. As a result, Wi-Fi users will have little chance to sense a clear channel and transmit. For more details about LTE channel usage and access procedures, refer to [13], [17]–[19], and [22]–[24].

Studying the MAC implementation of Wi-Fi system can help understand how LTE and Wi-Fi systems can coexist with each other. In fact, the LBT scheme introduced by [46] and [47] is a simplified version of DCF. In order to enable the coexistence of LTE-LAA and Wi-Fi in unlicensed bands, in such markets where the LBT is mandatory,

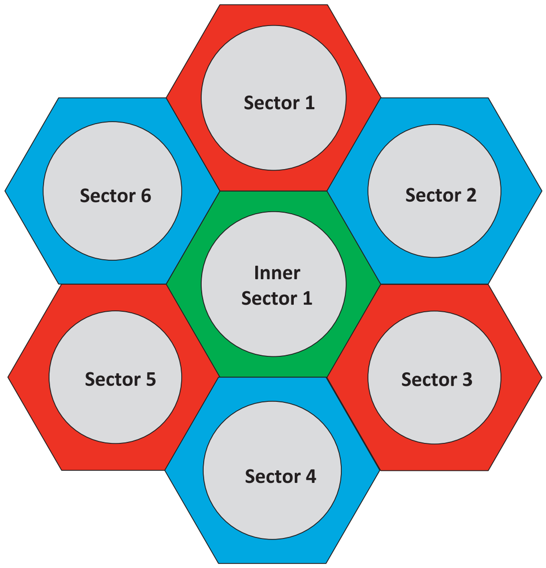

Fig. 3. Two categories of ICIC users: a) Cell Center User (CCU); b) Cell Edge User (CEU). CCUs are distributed in the gray region. CEUs are distributed in the color regions. CCU's frequency reuse factor is 1. The frequency reuse factor for CEU is 3. Different colors represent different frequencies.

the coexistence of these two systems can be enabled by LBT enforced on LTE-LAA in unlicensed bands [45].

Two design options of LTE-LAA LBT, asynchronous LBT and synchronous LBT, have been proposed in [48]. The main difference between them lies in that the asynchronous LBT is based on the current DCF protocol. In this case, the LBT scheme might use IEEE 802.11 RTS/CTS signals to ensure that the channel is idle just at that moment. However, synchronous LBT can be seen as a special version of asynchronous LBT, wherein, data subframes are synchronized with the licensed LTE carrier. This LBT approach may need a smaller number of changes in the LTE specification, and use Inter-cell Interference Coordination (ICIC) already defined in LTE releases to manage the interference among LTE base STAs [49].

A simple way to explain ICIC is based on the scheme of Fig. 3. The users are divided into two categories, one is CCU shown in Fig. 3(a), and the other is CEU shown in Fig. 3(b). CCUs are the users distributed in the gray region of Fig. 3, and CEUs are the users distributed in the red, green and blue areas. CCU can use all the frequency points to communicate with the base STA, while CEU must use corresponding specified frequency points to ensure orthogonality between different cells. CEUs can be assigned a higher transmission power for the frequency reuse factor greater than 1. The frequency points are not overlapped at the edges so the adjacent cell interference is small. CCU's frequency reuse factor is 1 for the cases where path loss is small and transmission power is low. Therefore the interference to the adjacent cells is not high either. More details about ICIC can be found in [19], [50], and [51].

Furthermore, LTE advanced in unlicensed spectrum can also use a coexistence mechanism centralized by CSAT, which is in spirit very similar to DCF.

Moreover, enhanced ICIC (eICIC) in 3GPP Release 10 [38], which is designed to mitigate intra-frequency interference by using various measures in the power, frequency, and also time domain, introduces a concept of Almost Blank Subframes (ABSs) to manage coexistence of the two technologies [52]. ABSs are LTE subframes with reduced DL transmission activity or power. The eICIC in time domain introduces a Resource Specific Cell Selection (RS-CS) method. The concept is to have certain sub-frames during which the Macro-eNB is not allowed to transmit data allowing the Pico cell edge users suffering high interference from the Macro-eNB, to be served with better conditions. Transmissions from Macro-eNBs are periodically muted during entire sub-frame. The users associated with the Pico cell can send their data during such an ABS and avoid interference from the Macro cell. In fact the muting is not completed since certain control signals still need to be transmitted even in the muted sub-frames to avoid radio link failure.

E. Key Factors of Performance Difference Between LTE-LAA and Wi-Fi

Mobile operators are assessing LTE-LAA in the 3GPP standardization. At the same time, Wi-Fi also relies on for enterprise and residential offload, carrier Wi-Fi, or hotspot access, and the use of this technology expanding as Wi-Fi becomes more preferable while using unlicensed spectrum for opportunistic access. Since LTE in unlicensed band will be deployed mostly in SC topologies, often in indoor locations, operators can face a complex decision of choosing between LTE-LAA and Wi-Fi especially when they plan for an SC deployment [53]. In some deployment scenarios, if practical commercial factors are taken into account, LTE-LAA or Wi-Fi should be used alone in 5 GHz band without considering coexistence issue. Even if the coexistence issue is considered, LTE-LAA and Wi-Fi deployments should also depend on their own features. Therefore, comparison of performance between LTE-LAA and Wi-Fi becomes necessary. In order to emphasize key points, we choose several items of representative performance to illustrate the difference between two RANs.

1) Spectral Efficiency: The following factors are responsible for the improved spectral efficiency of LTE-LAA over Wi-Fi:

a) *Robust transmission schemes:* As stated before, LTE is a synchronous system and uses scheduling-based channel access rather than contention-based random access. LTE-LAA adopts centralized MAC layer to schedule multi-user transmissions based on the user feedback information of the channel qualities, achieving multi-user frequency-selective diversity gain [10], [16], [21].
b) *Effective interference management:* Interference coordination and avoidance mechanisms, i.e., eICIC and Coordinated Multi-point (CoMP) are adopted in LTE systems to reduce interference and improve spectrum efficiency. CoMP transmission and reception actually refer to a wide range of techniques that requires close coordination among a number of geographically separated eNBs. They dynamically coordinate to provide joint scheduling and transmissions as well as proving

joint processing of the received signals. In this way a user at the edge of a cell is able to be served by two or more eNBs to improve signals reception and transmission as well as increase throughput particularly under cell edge conditions [14], [15], [24], [38].

c) *Carrier aggregation to manage traffic across licensed and unlicensed channels:* LTE carrier aggregation technology, aggregating both licensed bands and unlicensed band, will bring in several benefits. First, higher throughput can be achieved with the help of a wider bandwidth. Second, aggregating multiple carriers not only increases spectrum but also includes trunking gains from dynamically scheduling traffic across the entire spectrum. This in turn increases cell capacity and network efficiency as well as improves the experience for all users. Third, carrier aggregation also leads to an optimum utilization of the operator's spectrum resources. The majority of operators has fragmented spectrum covering different bands and bandwidth. Carrier aggregation helps combine these into more valuable spectrum resource [12], [13], [18].

d) *Better mobility and coverage support:* As stated in Section III-C, LTE-LAA users are operated within a unified architecture since LTE access methods can be used on both licensed and unlicensed spectrum [4]. First, a unified architecture means the same core network, and the same integrated authentication, management, and security procedures. Second, synchronization on both spectrum types means that interference bursts can be handled better. Last but not least, PCells can always provide ubiquitous coverage for one user. Only horizontal handover is needed between SC and Macro cell [19], [22], [23].

e) *HARQ versus ARQ:* As for the difference of retransmission mechanisms between LTE and Wi-Fi, LTE can make full use of time-domain receiver diversity with the help of Hybrid Automatic Repeat Request (HARQ) at MAC layer, which has a higher efficiency than single-loop ARQ with ACK used by Wi-Fi due to the receiver combination of retransmissions and small overhead [30]. For ARQ, if the received data has an error (as detected by ARQ) then it is discarded, and a new transmission is requested from the sender. For HARQ, if the received data has an error then the receiver buffers the data and requests a re-transmission from the sender. In this case the eNB will perform a retransmission, sending the same copy of the lost packet. Then, the user will try to decode the packet combining the retransmission with the original version, and will send an ACK message to the eNB upon a successfully decoding [11], [20], [24].

2) Link Adaption: In terms of link adaption, Wi-Fi uses open-loop link adaption without asking for Channel Quality Indicator (CQI) feedback, hence it is incapable of catching up with fast channel/interference fluctuation. On the contrary, LTE can choose resource blocks based on the received CQI [54]. Another impact of using dynamic link adaption based on instantaneous CQI feedback is that, if both technologies employ the same power, the Power Spectral Density (PSD) for LTE is higher than that for Wi-Fi. PSD describes how power of a signal or time series is distributed over frequency, as defined in [55]. This also means, to attain the same PSD, the power consumption of LTE will be much lower than that of Wi-Fi. Power consumption often refers to the electrical energy over time supplied to operate an electrical appliance.

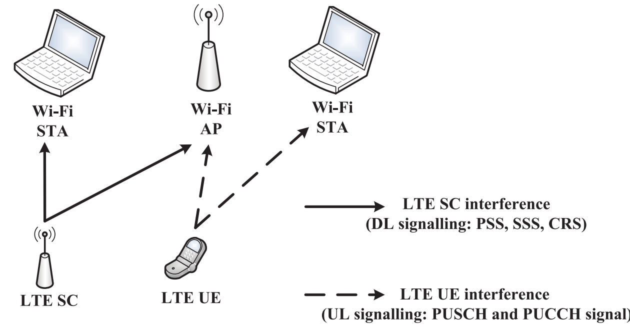

Fig. 4. Co-channel interference from LTE SC/UE to Wi-Fi AP/STA.

3) Performance Stability: As stated in Section III-B, for LTE-LAA, licensed and unlicensed bands are integrated on the same SC, and only the PCell can carry the control signallings which are granted the highest priority among the nine QoS class identifiers the LTE has defined. The control channel messages are transmitted properly between the base STAs (BSs) and the users. Those features make LTE-LAA be able to better facilitate the opportunistic unlicensed access. Wi-Fi systems, on the contrary, is not efficient especially when the network is heavily loaded [10], [11], [20].

4) Additional Wi-Fi Advantages: Compared to LTE-LAA, Wi-Fi has several advantages. Besides its robust standardization and established ecosystem, an additional advantage is its wide Access Point (AP) footprint in the enterprise and in public venues [53]. This installed base can be used as a springboard for SC deployment. Being able to co-locate SCs where Wi-Fi APs already exist can speed up deployments and reduce cost and complexity in the above two scenarios. On the contrary, while combining unlicensed and licensed LTE strategy, a mobile operator may find it more complex to gain access to these premises, because enterprise and public venues managers already have their own Wi-Fi networks. An operator wanting to install LTE unlicensed might be taken as an aggressive competitor, especially if the fair coexistence of LTE-LAA and Wi-Fi is not trusted [56].

F. Co-Channel Interference

1) Interference Sources: Fig. 4 shows two sources of potential co-channel interference caused by LTE-LAA to the Wi-Fi APs in cases where LTE-LAA SCs are deployed with Wi-Fi APs together [57]. One source of co-channel interference is DL signaling from the LTE SC. This signaling includes not only broadcasted synchronization and discovery such as the Primary Synchronization Signal (PSS), Secondary Synchronization Signal (SSS) and Cell-specific Reference Signal (CRS), but also data transmissions to users. This interference will impact the Wi-Fi AP as well as the STA. Another source of co-channel interference is UL signaling including control information such as the PHY UL Shared Channel (PUSCH) signal and PHY UL Control Channel (PUCCH) signal from the user.

2) Interference Management in Unlicensed Bands: One crucial issue for LTE-LAA and Wi-Fi coexistence mechanisms reviewed above is the so-called interference management, including interference detection, measurement and mitigation/avoidance, etc.

Take the LTE-LAA interference management in unlicensed bands for Wi-Fi operation for example. One method for improving the quality of interference management has been provided in [35]. The basic idea is to compare the signal energy monitored by Wi-Fi devices with a known waveform signature corresponding to LTE-LAA operation. The comparison result works as an indicator to help identify the presence of an LTE-LAA interferer on the communication channel in the current frequency band.

In particular, first, the Wi-Fi AP monitors signalling energy on a communication channel in a frequency band associated with its typical operations, such as the 5 GHz. Wi-Fi is able to monitor signalling energy within its frequency band of operation by using its own WLAN receiver circuitry. Second, once the measurements are collected, the Wi-Fi AP can compare the monitored signal energy with a known waveform signature corresponding to LTE and identify therefrom the presence of any LTE interfaces. For example, PSS and SSS signals are sent on the center subcarriers of all component carriers in the last Orthogonal Frequency Division Multiplexing (OFDM) symbol of the 1st slot and 11th slot in every RF by the LTE SC. The periodicity of the signaling energy output in center frequency bins can accordingly be matched in pattern to identify the presence of nearby LTE SCs based on a PSS and SSS signature pattern. Then, the interference identification may be repeated over a period of time to produce reliable pattern matching results. Finally, once an LTE interferer has been identified, the Wi-Fi AP may perform further match processing on the resulting signal energy pattern to classify the type of interference [57].

G. Summary and Guidelines

1) Lessons Learnt From LTE and Wi-Fi MAC Comparison: In general, LTE and Wi-Fi adopt different MAC layers.

From the aspect of channel access and channel usage schemes, for LTE systems, there are no sensing and backoff procedures. Instead, in LTE systems designed for licensed bands, there indeed exists a centralized controlling architecture, which always allocates one resource unit to the user that can maximize the target metric in every subframe. A Wi-Fi node, on the contrary, with no need for centralized controller, will first sense the channel whenever it has a pending transmission.

What's more, for Wi-Fi systems, channel is occupied only when packets need to be transmitted. Since LTE frames are contiguous, channels are always in the ON periods.

Furthermore, channel access in LTE systems are centrally scheduled, so the collision avoidance mechanisms adopted in Wi-Fi is not required in this case.

2) The Choice of LTE-LAA and Wi-Fi: In addition to the key factors of performance difference between LTE-LAA and Wi-Fi summarized in Section III-E, there are still two issues with the heaviest weight of consideration during the choice procedure:

a) Wi-Fi still needs enhancement in coverage, mobility and network efficiency like what LTE offers [9]. Unlike Wi-Fi, LTE network is well integrated to the existing operator network, thus solving almost all authentication, operations and management and QoS issues [7]. LTE also simplifies network management and tracking of key performance indicators through a single RAN [58]. Unfortunately, due to various types of restriction upon large-scale transformation towards Wi-Fi, it seems impossible to achieve the purpose of above-mentioned enhancement on Wi-Fi performance in the foreseeable future.
b) Wi-Fi has been widely used with traditional merits in low cost and easy deployment, making the integration of Wi-Fi in LTE networks possible today. Furthermore, the commercial availability of LTE-LAA in mobile devices requires a couple of years [53].

When operating in a channel shared with Wi-Fi or another LTE-LAA network, LTE's performance advantages are reduced by interference or by the introduction of coexistence mechanisms. For more details about how coexistence mechanisms affect performance of LTE-LAA and Wi-Fi, refer to Section IV-D.

In view of their own benefits, the choice of Wi-Fi or LTE-LAA should depend on the environment and power considerations. The detailed environment classifications are being elaborated in Section IV. Furthermore, it is also related to the experience of operators and even financial and other factors.

This section includes an overview of the recent existing literature on LTE and Wi-Fi coexistence in 5 GHz. For details about performance evaluation workflow, scenarios and metrics, refer to Section IV-C.

IV. Current Research on LTE-LAA and Wi-Fi Coexistence Considerations

In light of the aforementioned challenges, this section first overviews the recent related works to present a stage picture of the research in the community. What's more, representative coexistence mechanisms with and without LBT features will be investigated from the markets perspective. In addition, we further summarize and compare between these two kinds of schemes in terms of MAC/PHY modification requirement, advantages and disadvantages. Moreover, we illustrate lessons learnt from cognitive radio, as well as recommendations and guidelines for ensuring fairness.

A. Recent Related Works

This section includes an overview of the recent existing literature on LTE and Wi-Fi coexistence in 5 GHz. For details about performance evaluation workflow, scenarios and metrics, refer to Section V-C.

TABLE III
COMPARATIVE STUDY OF COEXISTENCE SCHEMES

Item	Scheme	Descriptions	Characteristics/limitations
[9]	LTE UL power control	**The design of an LTE UL power control** with an interference-aware power operating point.	1. LTE power control procedures are specified and established by 3GPP TS 36.213 [59]. 2. LTE UL power control defines UE transmit powers so that path loss and interference are compensated. 3. Not suitable in dense deployment scenarios.
[25]	LBT	**The design of three LBT design options:** 1. LBT without random backoff; 2. LBT with random backoff in a contention window of fixed size; 3. LBT with random backoff in a contention window of variable size (The 3rd option is also adopted by [60]–[62]).	1. Lower collision probability means higher Wi-Fi throughput. 2. The collision probability to the Wi-Fi can be adjusted by the contention window size. 3. Wi-Fi performance itself benefits from a variable backoff periods.
[45]	LBT	**A specific LBT scheme considering two data rate stages:** 1. At high data rate stage, if packet collision occurs, the equipment will not transmit, and LTE-LAA will automatically go to low data rate stage; 2. At low data rate stage, LTE-LAA will use a lower modulation and coding selection.	1. Much simpler compared to previous LBT schemes. 2. Not included in the 3GPP discussion. 3. The definition about high/low data rate stage is not easy to use.
[46], [47]	LBT	**The design of a LBT scheme similar to Wi-Fi**: 1. Based on the Wi-Fi DCF protocol; 2. Similar to Wi-Fi CSMA mechanism (section IV.C.2).	1. Only holds when the coexistence channel model can accurately simulate the interference condition. 2. This LBT approach needs a large number of changes in the LTE specification.
[48]	LBT	**The design of two LBT options:** 1. asynchronous LBT (similar to [46], [47]); 2. synchronous LBT (data subframes are synchronized with the licensed LTE carrier).	1. The asynchronous LBT scheme might use IEEE 802.11 RTS/CTS signals to ensure that the channel is idel; 2. The synchronous LBT scheme may need a smaller number of changes in the LTE specification, and use ICIC to manage the interference among LTE STAs.
[63], [64]	LBT	**The design of two LBT options:** 1. frame-based LBT, where the equipment has an idle period after transmission; 2. load-based LBT, where the equipment checks the channel, and transmits if the channel is idle (also adopted by [65], where LTE-LAA further incorporates a backoff defer period after a busy channel has just become free).	1. Since LTE operates with the fixed frame period, the frame-based LBT is easy to be applied in LTE if a fixed frame period for frame-based LBT can be defined. 2. Load-based LBT takes the advantages over frame-based LBT in channel access opportunities because the transmitter can continuously detect the channel.
[66], [67]	LTE muting	**Assigning channel time** to every competing entity including idle periods, successful transmissions and collisions for the Wi-Fi network.	1. Wi-Fi performance will degrade because Wi-Fi UEs may spend. much time in backoff. 2. The above problem can be solved if LTE-LAA can exploit the silent time. 3. ABS can be exploited as a base (section IV.B.2) in order to avoid interference from LTE-LAA to Wi-Fi.
[68], [69]	CHS	**CHS** performs scanning procedures to classify the different channels based on their conditions. (section IV.B.1)	1. Sufficient if the traffic density is low. 2. Not available if there is no clean channel.
[37]	CSAT	The key idea of **CSAT** is to define a time division multiplexing cycle for the LTE-LAA transmission in a short term (section IV.B.1).	1. As a supplement to CHS 2. For characteristics and limitations, refer to Table VI

1) An Overview of Coexistence Mechanisms Related Researches: There are some existing works studying the coexistence mechanisms of LTE-LAA and Wi-Fi networks in very recent years. Relevant studies in this paper are overviewed in a logical manner.

The community first analyzes the problem of LTE-LAA and Wi-Fi coexistence. For example, in [70], coexistence of LTE-LAA and Wi-Fi in the TV white space band is studied. Simulation results show that in situations where LTE and Wi-Fi nodes are randomly deployed, Wi-Fi throughput can be significantly degraded by LTE interference. In [71], the results show that channel sharing between Wi-Fi and LTE is unfair for the Wi-Fi network to a great extent.

To solve the above challenges, the basic idea of enabling the fair coexistence of LTE-LAA and Wi-Fi networks by adjusting LTE MAC protocols is proposed. In [46], it concludes that LTE-LAA can gain high throughput performance without harming Wi-Fi performance with the proposed MAC mechanisms. However, this conclusion only holds when the coexistence channel model can accurately simulate the interference condition between LTE-LAA and Wi-Fi transmission. Papers like [37] mathematically model how LTE would behave if quite period was added to it. They calculated the probability of Wi-Fi's back-off delay is less than LTE-LAA quite period. However, in this paper, authors only consider pure statistical approach, and eliminate PHY layer effects as well as hidden/exposed terminal problems. Papers like [66] suggest to divide transmission burst time. This means that the BSs must know the exact number of nodes of LTE-LAA and Wi-Fi. This is challenging if nodes overhear each other.

Then, coexistence mechanisms designed for markets with or without LBT requirement are proposed. Table III shows

TABLE IV
PROGRESS IN LTE UNLICENSED STANDARDIZATION [53]

Time	Description
Dec. 2013	Qualcomm and Ericsson presentation of the initial proposal for LTE-U at a 3GPP meeting.
Jan. 2014	A 3GPP unofficial meeting with companies and operators presenting their perspectives on the use of LTE in 5 GHz.
Mar. 2014	**Outcomes include:** 1. A plan to set up a study item in September 2014. 2. Adoption of LTE-LAA designation Agreement to focus on the 5 GHz band. 3. Commitment to finding a global solution. 4. Establishment of fair coexistence with Wi-Fi and among LTE operators.
Sep. 2014	3GPP approves LAA-LTE as a study item for Release 13. The main goal is to determine the changes needed for fair coexistence of LTE-LAA and Wi-Fi. **The relevant study covers:** 1. Regulatory requirement 2. Deployment Scenarios 3. Design targets and functionalities 4. Coexistence evaluation and methodology **Required functionalities include:** 1. LBT mechanism 2. Dynamic frequency selection for radar avoidance 3. Carrier selection 4. Transmit power control
Mar. 2016	Complete **LTE-LAA related Updates:** 1. LBT coexistence mechanisms implementation design 2. The paring of unlicensed transmission with licensed band **Other LTE Unlicensed Updates:** 1. LTE-WLAN Radio Level Aggregation (LWA) is included in Release 13. 2. New functionality to improve mobility management. 3. eNB management in integrated LTE and Wi-Fi network. 4. 3GPP has approved Enhanced LTE-LAA and Enhanced LWA in Release 14, targeting completion by June 2017.

a comparative study of coexistence schemes proposed so far. Papers like [30], [46], [59], [65], and [72] introduce coexistence algorithm by implementing contention based algorithms in LTE-LAA, i.e., LBT, and add collision avoidance algorithms to LTE-LAA. Specifically, 3GPP is working on the introduction of LBT in the 3GPP standards. Progress in LTE-LAA standardization is shown in Table IV. 3GPP has also defined an LTE-LAA coexistence mechanism in TS 36.213 [59]. An extensive coexistence study of different coexistence mechanism has also been summarized in 3GPP TR 36.889 [72]. However, as will be stated in Section IV-D, LBT introduces extra delay due to the contention time overhead, which can lead to inefficient channel usage.

For markets with no LBT requirement, authors in [68] and [69] propose a Channel Selection (CHS) mechanism to enable the coexistence of LTE-LAA and Wi-Fi. However, as discussed in Section IV-B, LTE-LAA has to hold until the channel becomes idle again in scenarios where no clean channel is available. As a supplement to CHS, CSAT is proposed in [37]. The advantage and drawback of CSAT as well as other duty-cycle mechanisms can be found in Section IV-D1. An approach using LTE UL power control to solve the coexistence issue of LTE-LAA and Wi-Fi networks is studied in [9]. Simulation results show that the proposed power control mechanism can improve the performance of both types of networks. However, power control mechanism can not solve coexistence problem of LTE-LAA and Wi-Fi in dense deployment scenarios.

2) An Overview of LTE-LAA and Wi-Fi Coexistence Testing and Results: LTE-LAA and Wi-Fi coexistence physical equipment studies and simulations have been presented by a number of industry players. Their testing activities are hardly in the form of apples-to-apples comparisons, particularly in recent comments to the Federal Communications Commission (FCC). That is due to the fact that different companies are calling the other's test methodologies skewed toward their preferred results. What's more, testing organised by the industry consortium LTE-U Forum is mainly focused on mechanisms designed for markets without LBT requirement. On the contrary, testing organised by 3GPP are aimed at markets with LBT requirement. Unlike the former two others, test works organised by Wi-Fi stakeholders is focused on ensuring that technologies share unlicensed spectrum fairly with Wi-Fi. This section summarizes what different companies have concluded based on their evaluations from different angles.

In comments to the FCC, there are different kinds of suggestions. The first kind is to leave the development of coexistence mechanisms to industry cooperation with the broader unlicensed community, e.g., IEEE 802.11 and the Wi-Fi Alliance rather than regulatory intervention. For instance, in [73], tests are conducted in an RF isolation chamber with programmable attenuators, with single Wi-Fi AP-client pairs and a single LTE-LAA eNB. Only LTE-LAA transmissions in the unlicensed bands were considered. It concludes that the failure to coexist effectively can be attributed to two factors. One is the effect of LTE-LAA's duty-cycling mechanism on Wi-Fi operation, as will be discussed in Section IV-D. Another is the lack of effective coexistence mechanisms in scenarios where LTE-LAA and Wi-Fi devices receive signals from each other at moderate levels. It even states that LTE-LAA does not have an effective coexistence technique to handle scenarios in which LTE-LAA and Wi-Fi devices hear each other at moderate levels (below -62 dBm) and, as a consequence, Wi-Fi can be crippled in such scenarios. Nevertheless, the accuracies of this claim have been contested by [74], which reflects the second kind of suggestion that LTE-LAA is a better neighbor to Wi-Fi than other Wi-Fi devices. There are also some neutral opinions. In [75], a series of tests and demonstrations using eight Wi-Fi routers and gradually changing nodes in form of Wi-Fi or LTE-LAA have been done, arguing that it is unfair to compare Wi-Fi's performance in an interference-free environment to its performance in the presence of LTE-LAA. Instead, a more fair comparison is to evaluate Wi-Fi's performance in the presence of other Wi-Fi nodes. One thing [75] makes clear is that different vendors will be impacted quite differently in the presence of LTE over unlicensed band. There is further a very large set of FCC fillings within this area [78]. Furthermore, in [76], a significant amount of LTE-U forum testing and technical documentation can be found. However, the most crucial details such as the simulation models are proprietary. The testing has shown result that LTE-LAA behaves as a comparable neighbor to Wi-Fi compared to Wi-Fi as a neighbor, while LTE-LAA significantly outperforms Wi-Fi. All tests in [76] are based on the current IEEE 802.11ac standard.

TABLE V
TYPICAL LTE-LAA AND WI-FI COEXISTENCE TESTING AND RESULTS

Item	Organiser	Characteristics/conclusions
[73]	FCC	**The first representative suggestion:** 1. Leave the development of coexistence mechanisms to industry cooperation with the broader unlicensed community. 2. The failure to coexist effectively can be attributed to: a. Duty-cycling's effect on Wi-Fi; b. Lack of coexistence mechanism at moderate levels.
[74]	FCC	**The second representative suggestion:** 1. Congests [73]'s second conclusion. 2. LTE-LAA is a better neighbor to one Wi-Fi than other Wi-Fi devices.
[75]	FCC	**Neutral opinion compared to [73], [74]**: 1. Unfair to compare Wi-Fi's performance in an interference-free environment to its performance in the presence of LTE-LAA. 2. Instead, a more fair comparison is to evaluate Wi-Fi's performance in the presence of other Wi-Fi nodes. 3. Different vendors will be impacted quite differently in the presence of LTE in 5 GHz.
[76]	LTE-U Forum	**For markets without LBT**: 1. Simulation models are not published. 2. LTE-LAA behaves as a comparable neighbor to Wi-Fi compared to Wi-Fi as a neighbor, while LTE-LAA significantly outperforms Wi-Fi. 3. All tests in [76] are based on the current IEEE 802.11ac standard.
[72]	3GPP	**For markets with LBT**: 1. It is possible for LTE-LAA with LBT scheme in 5 GHz to be a good neighbor to Wi-Fi. 2. All testing activitis in [72] are based on the current IEEE 802.11ac standard. 3. Recommendations based on testing: a. Some LBT schemes should be configurable within limits b. LTE-LAA should support UL LBT.
[77]	Wi-Fi Alliance	**A future test plan:** 1. Tests are developed to ensure fairness to Wi-Fi. 2. How LTE-LAA equipment passes those tests is immaterial.

In addition, in [72], the testing work organised by 3GPP presents the results of a study on the operation of LTE in unlicensed spectrum as an SCell. It shows that with proper and robust coexistence mechanisms, it is possible for LTE-LAA with LBT scheme in 5 GHz to be a good neighbor to Wi-Fi. For example, LTE-LAA causes less adjacent channel interference to a Wi-Fi system compared to another Wi-Fi system. 3GPP also provides some recommendations for the coexistence study in the future based on the testing result. First, it is recommended that the key parameters of the LBT scheme such as contention windows and defer periods should be configurable within limits to enable fair coexistence with other technologies operating in unlicensed spectrum. Second, it also shows that LTE-LAA should support UL LBT at the UE.

What's more, to ensure that LTE-LAA and Wi-Fi will coexist well and to address stakeholder questions and concerns, LTE-U Forum has been collaborating with Wi-Fi stakeholders, e.g., the Wi-Fi Alliance, CableLabs and others in the cable industry. In particular, Wi-Fi Alliance has posted the current test plan [77], and also posted the coexistence guidance [79]. In [77], tests are developed to ensure fairness to Wi-Fi, and how LTE-LAA equipment passes those tests is immaterial and is not specified. Table V gives the details of each work.

B. Coexistence Mechanisms in Markets Without LBT Requirement

In those markets where no LBT is required, with carefully designed coexistence mechanisms, resource sharing between LTE-LAA and Wi-Fi in unlicensed band could be managed fairly without modifying Release 10/11 PHY/MAC standards. LTE-LAA duty cycling is proposed to release resources to the Wi-Fi network. One practical way to implement duty cycling is using coexistence mechanism centralized by CSAT [2], [6]. Another feasible methodology is assisted by ABS [70], [71], [80].

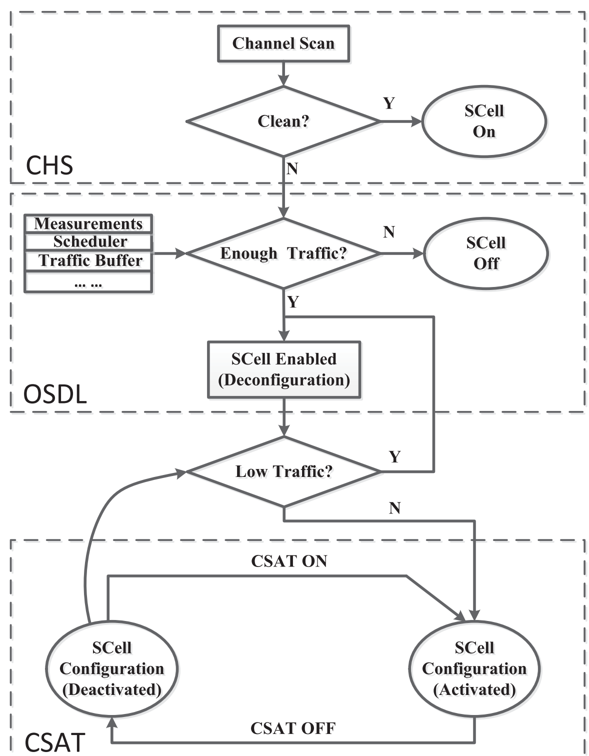

Fig. 5. Three steps of coexistence mechanism centralized by CSAT [2]: a) CHS; b) OSDL; and c) CSAT.

1) Coexistence Mechanism Centralized by CSAT: One example cellular operation consisting of three different techniques has been given in [81]. As shown in Fig. 5, the whole

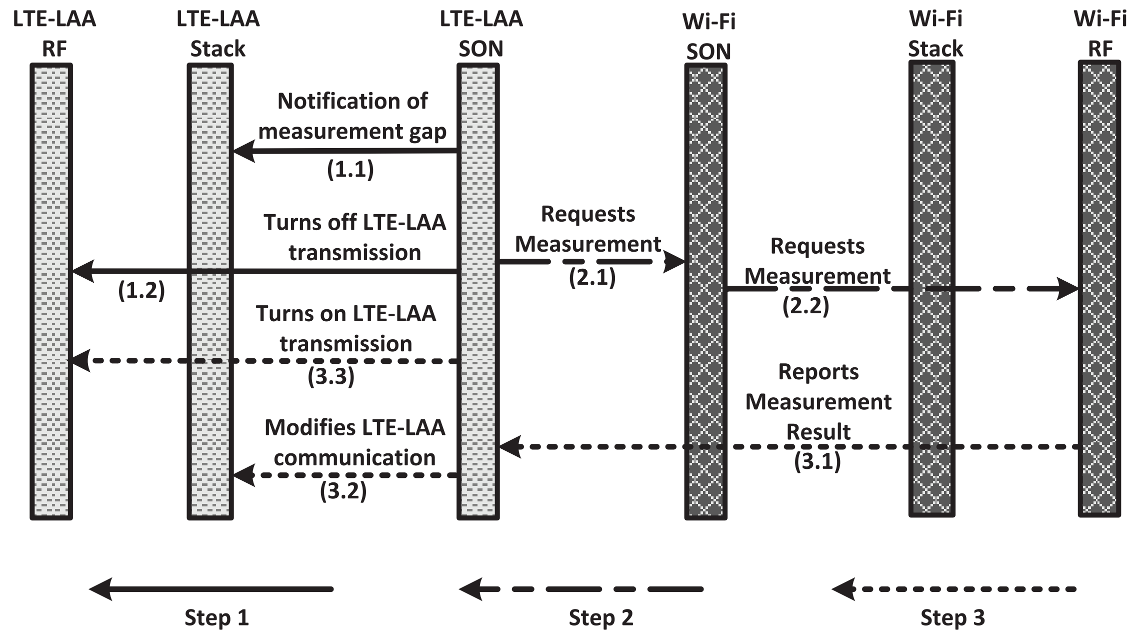

Fig. 6. Messages exchange between Co-located LTE and Wi-Fi radios [81].

workflow can be divided into three steps. Originally, the CHS performs scanning procedures to classify the different channels based on their conditions. If a clean channel is identified, a corresponding SCell (e.g., LTE-LAA) can be operated without concerning co-channel communications. In practice, if a form of interference is found in the current operating channel, the LTE-LAA transmission will be switched to a cleaner one with less interference by using LTE Release 10/11 procedures. Note the interference level in this example can be measured by energy detection for the sake of simplicity, as is done in [82], where interference types and sources are not considered. On the other hand, in consideration of the existence of multiple incumbent wireless technologies besides Wi-Fi in the unlicensed spectrum such as radar signal and satellite signal, a scheme of high level interference detection of which the sensitivity is improved by collecting the information of the sources types and quantities can be performed [4].

CHS is often sufficient to meet the Wi-Fi and LTE-LAA coexistence requirement as long as the traffic density is low [6]. On the contrary, in areas of dense deployments, where no clean channel is available, a further process, i.e., Opportunistic SDL (OSDL) should be utilized to reduce the impact on co-channel communications. Input from CHS algorithms as well as from various measurements, traffic buffers and schedulers is optional by OSDL to find out whether there exists enough traffic to support a secondary carrier or not. If the answer is 'YES', an SCell supporting relevant secondary carrier can be initially enabled in a deconfigured state, then be configured and activated with the help of additional process such as CSAT which is designed to improve the coexistence performance. Otherwise, if no enough traffic is available, SCell will be disabled [81].

CSAT has been proposed initially by Qualcomm for LTE-LAA MAC scheduling [6]. During CSAT operation, the SCell remains configured. However, once the traffic level drops below a certain threshold, the SCell will return to the deconfiguration state. The key idea of CSAT is to define a time division multiplexing cycle for the transmission of LTE-LAA in a short duration of time, where CSAT is enabled, namely CSAT ON periods, during which it is available for an SC to transmit at a relatively high power. While in the rest part, also known as CSAT OFF periods, although remains configured, the SC will operate at a relatively low power or even gate off in order to avoid competing with Wi-Fi [4].

Measurements of resource utilization performed by user devices and/or small BSs can be utilized as reference materials to help adapt the CSAT parameters accordingly [6], [81], [82]. In another word, one Radio Access Technology (RAT) (e.g., LTE-LAA) needs to request a measurement from another RAT (e.g., Wi-Fi) and to identify its utilization based on the received signals. Fig. 6 shows an example of about how messages exchange between two different RATs during measurements time [81]. The whole workflow also consists of three steps. In the first step, the LTE-LAA Self-organizing Network (SON) sends a message to the LTE-LAA stack to notify that a measurement gap is upcoming on the shared unlicensed band and then commands the LTE-LAA radio to temporarily turn off transmission on the unlicensed band. The purpose of this part is to guarantee that LTE-LAA transmission will not interfere with measurements during this time. Sequentially, LTE-LAA SON requests the co-located Wi-Fi SON that a measurement be taken on the unlicensed band by sending a message, which will then command Wi-Fi RF to measure how Wi-Fi is utilizing the unlicensed band currently. In the final step, the measurement report including the results of the measurements goes back to the LTE-LAA SON, which may send permission to LTE-LAA RF and LTE-LAA stack separately in order to turn on LTE-LAA transmission and modify communication.

By adjusting those parameters such as the cyclic on/off ratio and transmission powers during the CSAT ON or OFF periods

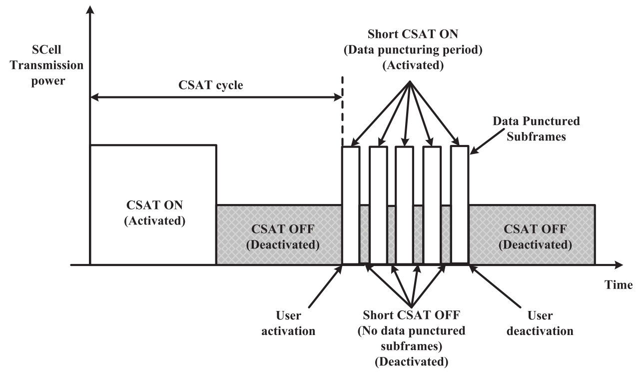

Fig. 7. Two categories of CSAT periods. (a) CSAT ON periods; (b) CSAT OFF periods. The usage of the channel by LTE-LAA radio can be reduced by pulling its transmission power back or bring the cyclic ON/OFF ratio down, and vice versa. The introduction of data punctured subframes can be used to reduce latency by dividing the CSAT ON periods into two parts: the short CSAT ON periods and the short CSAT OFF periods.

based on the current signaling conditions, resource sharing between LTE-LAA and Wi-Fi in the same unlicensed spectrum can be optimized, thus leads to a better coexistence performance. Take a representative CSAT communications scheme shown in Fig. 7 for example [81], if the utilization of a given channel by Wi-Fi devices needs to be high, the usage of the channel by LTE-LAA radio can be reduced by pulling its transmission power back or bring the cyclic on/off ratio down, and vice versa.

The CSAT ON/OFF period duration also differs in various solutions. In some articles like [81] this length of the CSAT cycle is designed to be greater than 200 ms to guarantee a sufficient opportunity for user devices to measure the channel condition at least one time. What's more, longer CSAT cycle means higher capacity because of less overhead in carrier activation [2]. On the flipside, shorter CSAT cycle reduces latency impact to delay sensitive traffic on Wi-Fi. Like what coexistence specification from LTE-U forum says, the maximum length of CSAT ON/OFF period is 50 ms [76]. Unfortunately, it is contradictory indeed about this time length issue, so far no authoritative result has been reached. In general, coexistence mechanisms centralized by CSAT herein may enjoy several advantages. One example is, as mentioned before, it ensures fair and efficient channel sharing between LTE-LAA node and Wi-Fi APs making use of CHS, OSDL and CSAT as a group. Another big benefit is that such mechanism does not bring any change to the underlying RAT communication protocol [6], [81]. It is no doubt that a weakness remains in CSAT itself, namely its longer latency compared to CSMA. To solve this problem, in one aspect, primary channel occupation by Wi-Fi APs needs to be prevented by CSAT [6]. On the other hand, data punctured subframes inserted periodically in Fig. 7 is also capable of minimizing latency impact [2]. In particular, the data punctured subframes makes the CSAT ON period shown ahead be able to be divided into two parts: the short CSAT ON period, i.e., the data puncturing period, and the short CSAT OFF period, i.e., the time period where no data will be transmitted.

2) Coexistence Mechanism Assisted by ABS: Another mechanism called LTE muting in spirit similar to CSAT has also been proposed, which is summarized as avoiding different RATs accessing the channel at the same time, i.e., in n of every 5 subframes, LTE-LAA needs to be turned off, and Wi-Fi users will replace LTE-LAA nodes in using channel resource [4]. Another example of fair allocation scheme is to assign equal channel time to every competing entity including idle periods, successful transmissions and collisions for the Wi-Fi network [66]. Moreover, Wi-Fi users may spend a lot of time in backoff if there are a lot of users trying to access the network at the same time. The Wi-Fi performance would not necessarily degrade if LTE-LAA could exploit those silent times [67]. In those examples, the communication among different network techniques, utilized to adapt CSAT parameters and cannot always be ensured when devices belong to different operators, is not required. These time-sharing coexistence techniques requiring LTE silent periods would exploit ABSs, a key feature introduced in Release 10 as a base [70]. ABSs are LTE subframes with reduced DL transmission activity or power. By muting the transmission power of the SCs in certain subframes, interference caused by Macro eNBs to Pico eNBs would be less in HetNets [4], [70]. Building on this work, a probability for LTE-LAA to access the channel is defined in [84]–[86]. A survey involving the summary of an example coexistence mechanism assisted by ABS has also been published [70]. It is concluded that LTE-LAA activities in unlicensed spectrum can be controlled with the help of a modified version of ABS, where UL and/or DL subframes can be silenced, and no LTE common reference signals are included. It is shown that Wi-Fi is able to reuse the blank subframes ceded by LTE, and that throughput increases with the number of null-subframes. However, since LTE throughput decreases almost proportionally to the number of ceded blank subframes, a tradeoff is established. Additional LTE performance degradation may be observed if blank subframes are nonadjacent, since Wi-Fi transmissions are not completely confined within LTE silent modes. However, if the duration and occurrence of LTE blank subframes is reported to Wi-Fi during the negotiation phase, Wi-Fi nodes may be able to conveniently confine their transmissions within blank subframes and thus avoid interference with LTE.

C. Coexistence Mechanisms in Markets With LBT Requirement

In many markets where LBT requirement exists, various modifications are required to adapt LTE PHY/MAC. For example, LBT using Clear Channel Assessment (CCA) to determine if a particular channel is available is needed to meet regional requirement. The concept of beacon signal is also introduced to reserve the channel for transmission following LBT [6].

A node having data to transmit should perform a CCA first to determine the availability of the spectrum band, i.e., whether the channel is clean or already occupied by other signals transmitted by other operators or radar. If clean channel is available, this CCA procedure will contend for use of the radio frequency spectrum band. Upon the successful first

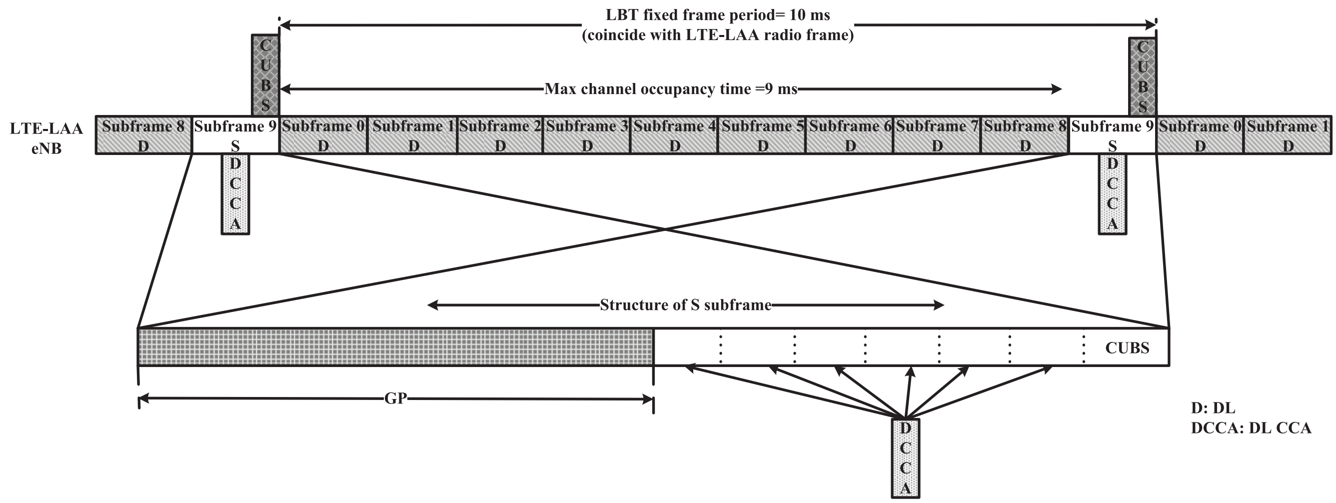

Fig. 8. An example of CCA placement option [83]. A subframe S (e.g., subframe 9) consists of a GP, several slots for CCA placement and a node for CUBS for the remaining symbols. A GP is provided prior to the CCA placement to guarantee the idle time. If the CCA procedure succeeds, the node will seize and hold the medium until the start of the next subframe S, and CUBS may block the transmission signals of other users nearby.

CCA procedure, one or more additional CCA procedures will be performed during Discontinuous Transmission (DTX) periods to determine continued availability of the radio frequency spectrum band [30], [87].

Fig. 8 shows a case of CCA placement options in an example of DL frame structure [83]. Subframe S (e.g., subframe 9) may be used to hold the succeeding transmission resources. It may work as CCA, DTX, or Channel Usage Beacon Signals (CUBS). A subframe S consists of a Guard Period (GP), several slots for CCA placement and a node for CUBS for the remaining symbols. A GP is provided prior to the CCA placement to guarantee the idle time. The number of slots for CCA placement varies in different papers, even as little as 2 in [69]. However, as is emphasized in [83], the number of slots for CCA placement may be referred to as a CCA reuse factor, which can be 3, 4, 7, 9 or 12. The reuse factor adopted in Fig. 8 is 7. If the CCA procedure succeeds, which means the node will grab and hold the medium until the start of the next subframe S, CUBS may block the transmission signals of other users nearby by notifying other nodes also performing CCA later in the same subframe S that the medium has been occupied.

It is necessary to set CCA threshold appropriately for the purpose of protecting nearby WLAN transmissions. The ability for devices to coexist is highly dependent upon their ability to detect another at lower RF levels. Raising the threshold helps protect smaller area around eNB and implies sensing. However, if the LBT threshold is too high, the case with LBT will become ineffective since it turns to be equivalent to the one without LBT. Lowing the threshold will lead to wider covering area, but reducing the chance for the eNB to transmit at the same time [30]. The CCA threshold also varies with two types of CCA techniques designed in IEEE 802.11 specification, energy based CCA and preamble based CCA. In the former case, the transmitter only measures the total received power and does not require any knowledge of the signal structure or packet format. The preamble based CCA, on the other hand, is the one achieved by a cross correlation module. In IEEE 802.11, the transmitter will declare the channel as busy when the total received power is larger than -62 dBm while using energy based CCA in 20 MHz. This threshold value changes to -82 dBm while using preamble based CCA. Since in LTE-LAA, either energy based CCA or preamble based CCA, or even both may be used, CCA threshold should also be set carefully in different scenarios [88].

During example DTX periods shown in Fig. 9 [87], upon the successful first CCA procedure, one or more second CCA procedures may be performed to determine continued availability of the radio frequency band. If the first CCA does not succeed, the eNB will not transmit, nor will it perform any CCA until the next transmission period, either. On the contrary, if it succeeds, while the second CCA procedures fail during one DTX period, the transmission will stop until a subsequent second CCA indicates that the radio frequency band is available again.

D. Summary and Guidelines

1) Lessons Learnt from Different Coexistence Mechanisms Comparison: In general, for markets where no LBT is required, LTE-LAA's primary coexistence mechanisms can be summarized as duty-cycling, i.e., cycling LTE-LAA through ON/OFF periods. The main advantage of duty-cycling is that it requires fewer changes from LTE and does not require any ad-hoc standardization effort. The availability is attractive to operators who need to increase capacity in a short term, especially if they plan to deploy LTE-LAA in environments where there are free channels are available and hence fair coexistence with Wi-Fi is easy to achieve.

However, duty-cycling itself has some weakness, as stated in Section IV-B, while using duty-cycling, it is the LTE-LAA cell that decides how much fairness to allow, and Wi-Fi networks can only adapt to the rules set by LTE-LAA. In other words, it is the LTE-LAA device that controls the ON/OFF cycle. Due to

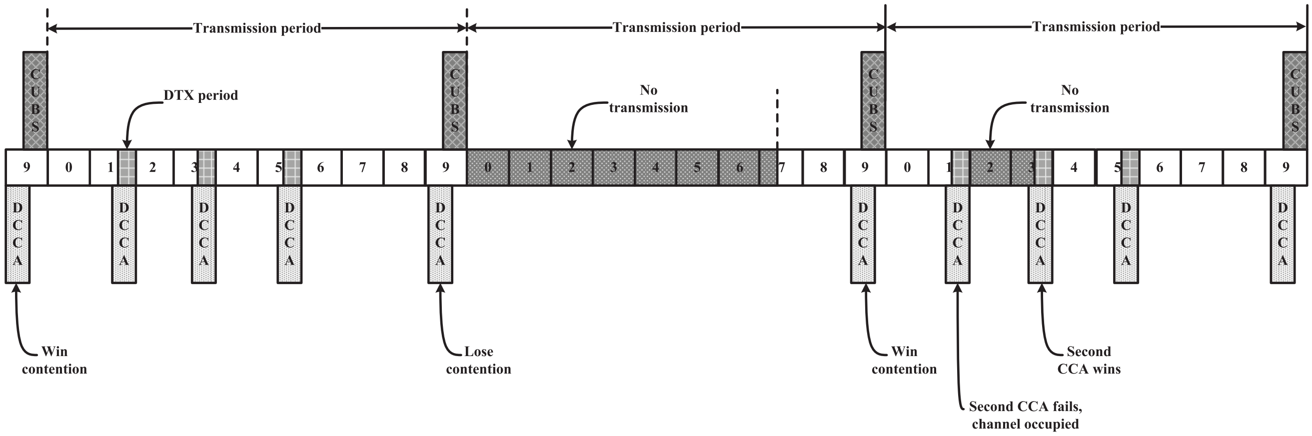

Fig. 9. Illustration of DTX periods and DL CCA intervals [83]. If the first CCA lose contention, the eNB will not transmit, nor will it perform any CCA until the next transmission period, either. On the contrary, if it wins contention, while the second CCA procedures fail during one DTX period, the transmission will stop until a subsequent second CCA indicates that the radio frequency band is available again.

this situation, duty-cycling may lead to a poor performance of Wi-Fi devices. Furthermore, although longer LTE-LAA OFF times can lead to a lower percentage of errors and thus excellent throughput, for a better delay and latency performance of Wi-Fi devices, shorter LTE-ON time is needed. LTE-LAA duty-cycle parameters may affect Wi-Fi performance, thus selection of cycle period is critical to the performance on Wi-Fi network [89]. As shown in Fig. 7, data gaps that can be punctured into data punctured subframes and inserted periodically are also capable of resolving this conflict by minimizing latency impact to delay sensitive traffic on Wi-Fi. However, new challenges will arise with the introduction of this method. First, the introduction of these gaps can exacerbate the rate control problem. Second, delay-critical frames may not be transmitted during the short gaps.

Compared to duty-cycling, the addition of LBT will bring several benefits. For example, LTE-LAA with LBT requirement will degrade performance and hence reduce the benefits of LTE-LAA over Wi-Fi, thus will improve Wi-Fi throughput [7]. What's more, LBT itself allows for a distribution of spectrum resources that takes the traffic load of each coexisting network into account. On the other hand, LTE-LAA with LBT also has some weaknesses. As stated in Table IV, the LBT standardization was just completed in March 2016, so LBT is more onerous to implement than duty-cycling. What's more, the impact of Wi-Fi would vary on how LBT is implemented. In fact, 3GPP designs four kinds of channel access schemes [25]:

a) *No LBT:* No LBT procedure is performed by the transmitting entity.
b) *LBT without random backoff:* It means the duration of time that the channel is sensed to be idle before the transmitting entity transmits is deterministic.
c) *LBT with random backoff in a contention window of fixed size:* The LBT procedure has the following procedures as one of its components. The transmitting entity draws a random number *N* within a contention window. The size of the contention window is specified by the minimum and maximum value of *N*. The size of the contention window is fixed. The random number *N* is used in the LBT procedure to determine the duration of time that the channel is sensed to be idle before the transmitting entity transmits on the channel.
d) *LBT with random backoff in a contention window of variable size:* The LBT procedure has the following procedures as one of its components. The transmitting entity draws a random number *N* within a contention window. The size of the contention window is specified by the minimum and maximum value of *N*. The transmitting entity can vary the size of the contention window when drawing the random number *N*, which is used in the LBT procedure to determine the duration of time that the channel is sensed to be idle before the transmitting entity transmits on the channel.

Wi-Fi performance itself benefits from a variable backoff periods. Nevertheless, 3GPP is also considering LTE-LAA using a fixed backoff periods. Table III further shows a comparative study of proposed LBT schemes.

Generally speaking, duty-cycling mechanisms are commonly regarded as being more aggressive and unfair than LBT because it does not abide by the same rules as Wi-Fi. However, adding LBT to LTE-LAA may takes away LTE advantages. It is also shown that the choice of channel access schemes real really makes sense, i.e., not all LBT schemes providing fair coexistence [25]. The introduction of LBT also requires MAC/PHY modifications, as discussed in Section IV-C. For more details, refer to Table VI.

2) Lessons Learnt from Cognitive Radio: To ensure fairness, the unlicensed spectrum is supposed to be shared without preference. Although coexistence mechanisms have been designed to ensure that the existing systems are minimally interfered, potential interference could still appear in existing systems. The interference will occur when primary system begins to transmit right or shortly after the secondary system starts the transmission. For different RANs in unlicensed spectrum, the Wi-Fi users can be regarded as the primary users (PUs) since Wi-Fi is the prevalent technology using 5 GHz. If subsequent users such as LTE-LAA users, referred to as

TABLE VI
COMPARATIVE STUDY OF LBT AND DUTY-CYCLING

	LBT	Duty-cycling
Advantage	More fair	1. Fewer changes from LTE; 2. No ad-hoc standardization requirement
Disadvantage	LTE performance degradation	Less Fair
Target Markets	With LBT reuirement (Europe and Japan)	Without LBT reuirement (UK, Korea and China)
Practicality	Release 13 was completed in Mar. 13, 2016; More onerous to implement	Based on Release 10-12; Can be deployed in a short term
MAC/PHY	Modifications required	Modifications required
Notes	1. Various LBT schemes (refer to Table III); 2. LBT implementation has an impact on coexistence performance; 3. LBT with random backoff in a contention window of variable size is more attractive to Wi-Fi.	1. Short gaps lead to not only short latency, but also rate control problem; 2. Cycle period is critical to the performance.

secondary users (SUs), want to use the occupied spectrum opportunistically or concurrently, an interference management mechanism should be established.

Since CR is initially designed in exploiting white spaces including unlicensed spectrum efficiently, it is nature to utilize the attributes of the CR to optimize LTE-LAA in 5 GHz. That means frequency-agile modems that can rapidly switch channels if interference is present, are needed.

The FCC defines CR as the radio that can change its transmission parameters based on interaction with the environment where it operates [90]. The main goal of CR is to identify the unused licensed spectrum for SU without causing interference to the PU. CR involves both spectrum sensing and channel switching techniques. Spectrum sensing is the ability to measure, sense and be aware of the parameters related to the radio channel characteristics. Spectrum sensing in CR networks is done for two purpose, one is to identify the spectrum opportunities, the other is to detect the interference in the spectrum. Channel switching techniques include predictive channel switching, random channel switching and optimal channel switching. Predictive channel switching mechanism calculates the remaining idle time of each channel and the channel with the largest remaining idle time is selected for switching. Random channel switching makes the selection in random manner when the interference occurs. In optimal channel switching scheme the channel that is free and offers longer remaining idle time is selected for switching.

LTE-LAA in 5 GHz can be regarded as a special case of OFDM-based CR systems. There are also several works focusing on LTE and LTE advanced networks along with CR. For example, in [91], CR is applied to sense the spectrum by using the conventional method of energy detection. In [92], the authors focus on improving resource efficiency in LTE network by considering CR device to device communication links. However, it seems the current available mathematically-optimal algorithms are not suitable for the implementation of LTE-LAA systems, due to potential iteration divergence and computation load [93]. We recommend that researchers focus on the LTE-LAA CR technique design.

3) Recommendations and Guidelines for Ensuring Fairness: Fairness is going to be the biggest sticking point, because of the lack of documented agreement on a definition of fairness. On the one hand, in [7], [28], and [25], fairness criteria means LTE-LAA should not impact Wi-Fi more than another Wi-Fi network, i.e., LTE-LAA node being brought into an existing system should not cause any more interference or degradation to a Wi-Fi than adding another Wi-Fi SC, only with respect to throughput and latency. Besides considering the fair coexistence with Wi-Fi, 3GPP also defines the fairness as the effective and fair coexistence among LTE-LAA networks deployed by different operators, which means that the LTE-LAA networks can achieve comparable performance, only with respect to throughput and latency [25]. On the other hand, we are also concerned that many 3GPP members might believe that fair access means the LTE-LAA BS should have half of the bandwidth and the IEEE 802.11 clients should have half of the bandwidth.

In general, LTE-LAA specifications may have to go beyond regulatory requirements to meet the levels of fairness that Wi-Fi stakeholders expect, namely that the impact of an LTE SC is not greater than that of a Wi-Fi AP. That is because of the fact that the standards body for LTE represents the mobile operator and vendor ecosystems and indirectly the Wi-Fi performance. The backoff time defined in LTE-LAA plays an important role in how the traffic will be split between Wi-Fi and LTE-LAA and, hence, is a factor in how fair the coexistence will be [53].

Nevertheless, an LTE-LAA standard that does not guarantee fair coexistence to Wi-Fi will not gain a sufficient level of industry-wide support. We provide several recommendations that may be useful to future research on fairness as well as the standardisation process for LTE-LAA in the unlicensed band.

a) *All technologies in the 5 GHz unlicensed band should have equal control for access to the medium:* Duty-cycling mechanisms targeting at the market with no LBT requirement allow the LTE-LAA to statically or dynamically define the proportion of a cycle allocated to LTE-LAA and the proportion allocated to Wi-Fi. It is unacceptable for an unlicensed spectrum that is supposed to be shared with preference. We recommend that any sharing scheme should treat LTE-LAA and Wi-Fi as equals in future decisions about medium access.

b) *LTE-LAA medium sharing algorithms should be dynamically designed, and respond quickly to changing conditions:* A static medium sharing algorithms like LTE muting discussed in Section IV-B can cause unfairness and inefficiency. We recommend that any unlicensed medium sharing algorithms should be designed to dynamically respond to the changing needs of all users. In addition, the CSAT ON/OFF period varies from 50 ms to 200 ms in past design. These designs are not able to meet the requirement of Wi-Fi, which is more reactive to changes in load and contention, adjusting on a packet by packet basis. We further recommend that any unlicensed medium sharing algorithms should be designed to respond to load changes within a few packets transmission.

c) *More complex tests on fairness, especially those based on a range of realistic usage scenarios are needed:* The tests and simulation already done by LTE-U Forum and 3GPP are only based on relatively simple scenarios [72], [76]. In particular, both LTE-U Forum and Wi-Fi evaluate the performance of LTE-LAA and Wi-Fi coexistence, only with respect to indoor/outdoor scenarios. In fact, as will be discussed in Section V-A, outdoor/indoor is just one of eight influential factors for the classification of SC scenarios. Studies in a range of realistic deployment scenarios and network densities are still missing. What's more, simulations done by 3GPP and LTE-U Forum consider limited traffic types. For example, It appears to be the simulation case with many obvious high density, high channel load missing from the set of simulations so far. In addition, there are some important metrics not captured in the current simulation and test, including packet loss, frame retransmission rate, packet loss and jitter, etc. We recommend researchers interested in this area refer to the performance evaluation metrics and scenarios organised in Section V, as well as test plan proposed by [77]. The community should also ensure that realistic simulation scenarios with both UL and DL traffic are considered.

d) *More researches on mechanisms for scenarios where LTE-LAA and Wi-Fi hear each other at a moderate interference level are required:* As discussed in Section IV-A, some industry members believe that there is no effective coexistence technique to handle scenarios where LTE-LAA and Wi-Fi devices hear each other at moderate interference levels [73]. There are some reasons for their understanding. First, the Wi-Fi devices are not aware of the duty-cycled nature of the interference. When the interference is below Wi-Fi's energy detection threshold, Wi-Fi will attempt to transmit, even in the presence of significant interference not formally detected by the Wi-Fi. Transmitting during LTE-LAA's ON time leads to greater error rates and causes Wi-Fi to slow down. Second, the LTE-LAA interference is on the same order as the Wi-Fi signal, so that while LTE-LAA is on, the Wi-Fi communication can be very limited, even not possible at all. In fact, if the Wi-Fi client and AP hear the LTE eNB below/above energy detection, respectively, a hidden node scenario where only a few Wi-Fi devices can transmit data frames will appear. Their conclusion is congested by the rest of the community [74], which explains that the divergence in results was caused by the fact that the testing done in [73] is based on extremely pessimistic and impractical assumptions. Their disagreement shows at least two shortcomings of current research. First, there is no unified version of the exact values of both LTE-LAA and Wi-Fi energy detection threshold. Second, there is no unified test platform for the coexistence. Our recommendation is that future researches should focus on solving the above two problems.

e) *The community should seek a balance between fairness and performance:* As stated above, coexistence such as LBT that increases fairness can have a negative effect on performance. The historical approach the Wi-Fi industry utilizes is to agree on the CSMA/CA access method instead of making an agreement on a definition of fairness. We recommend that LTE in the unlicensed band considers using a similar level of fairness that is common in Wi-Fi networks to reach a balance between fairness and performance.

f) *More researches concerning coexistence optimization are required:* In [37], fairness allocation between LTE-LAA and Wi-Fi is studied through theoretical and simulation analysis. However, literature is scarce and better mechanisms analysis might be needed. In general, while discussing the fairness, an objective function should be created to evaluate the user access or network serving. For markets with LBT requirement, researchers can refer the Wi-Fi scheduling fairness functions to create their own, since the LBT scheme is a simplified version of DCF. However, for markets without LBT, there is a need for new objective functions for optimization problem formulations to guarantee the fair coexistence of LTE-LAA and Wi-Fi. We also recommend researchers to optimize the coexistence of LTE-LAA and Wi-Fi separately rather than jointly. Optimizing LTE-LAA and Wi-Fi jointly requires information exchange between the two RANs, which further needs the LTE-LAA and Wi-Fi aggregation.

V. Deployment Scenarios for the Coexistence and Scenario-Oriented Decision-Making

In previous sections, some coexistence-related features of LTE-LAA and Wi-Fi, as well as typical coexistence mechanisms on 5 GHz are discussed. They are fundamental for the discussion and investigation of the coexistence of two principal technologies in wireless communication systems. In this section, representative scenarios of deployment, which are of great significance, are being classified for the purpose of decision making for the coexistence of LTE-LAA and Wi-Fi in the next step. The concept of 'scenario-oriented coexistence' is presented and highlighted by dissecting an example of deployment scenario.

TABLE VII
INFLUENTIAL FACTORS FOR THE CLASSIFICATION OF SC SCENARIOS

Influential Factors
With/without Macro Coverage
Outdoor/indoor
Ideal/non-ideal Backhaul
Sparse/dense SC Deployment
Synchronized/asynchronous Connection
Spectrum
Traffic
Backward Compatibility

A. *Influential Factors for the Classification of SC Scenarios*

As stated in 3GPP TR 36.932 [94], in principle, the deploying scenarios can be classified from perspectives of eight factors affecting scenario deployment features of SC. Table VII shows influential factors.

1) With/Without Macro Coverage: Since Macro layer plays an important role in guaranteeing mobility, an SC may benefit from the presence of overlaid Macro cells. On the other hand, in such cases as deep indoor situations, an SC should also be able to work without Macro coverage. Thus, even for a space of similar size and for a building of same architectural structure and interior furnishings, macro coverage will change deployment scenarios into different types compared with the case of absence of Macro cells.

2) Outdoor/Indoor: A key difference between indoor and outdoor scenarios is the mobility support. In indoor scenarios such as offices and apartments, users normally stay stationary or move at very low speeds. In outdoor scenarios, however, to cover a large area like park or garden, a large number of SC nodes need to be set up to guarantee mobility everywhere. Relatively higher terminal speed can thus be expected in this situation.

Table VIII shows another notable fact that some sub-bands of 5 GHz are only available for indoor environment, and some others are useful for both indoor and outdoor cases due to specific considerations of these countries [54].

3) Ideal/Non-Ideal Backhaul: While considering the potentially large number of Wi-Fi APs and/or LTE-LAA STAs to be deployed, the link connecting the RAN and core network, also known as the backhaul is another key aspect of scenarios classification. The ideal backhaul, e.g., dedicated point-to-point connection using optical fibre or Line of Sight (LOS), is defined as latency less than 2.5 ms and a throughput of up to 10 Gbps. All other types of backhaul are non-ideal. Fig. 10 shows examples of both ideal and non-ideal backhaul deployments [54]. The unlicensed and licensed carriers in ideal backhaul deployments can be co-located or connected with each other with the help of the Remote Radio Head (RRH). While deploying non-ideal backhaul deployment, Multi-stream Aggregation (MSA) can enable data transmission without the need for additional signalling, thus maximizing utilization of system resources even when the user moves between different cell identifications [95]. MSA leverages the centralized integration of multiple RATs, carrier and intra-carrier ports to improve cell-edge throughput. In particular, with inter-RAT MSA, different RATs can be utilized to enhance user experience. Take the LTE/Wi-Fi scenario for example, LTE can act the host layer, with Wi-Fi acting as the boost layer. The former provides basic mobile services to the user, with an LTE host link remaining connected with the user. Wi-Fi then enhances user experience by providing a boost link between the user and Wi-Fi AP to boost data transmission rates. In addition, with inter-frequency MSA, a user is always anchored to the Macro cell through a host link even while dynamic connecting to other carriers through boost links for enhanced data transmission.

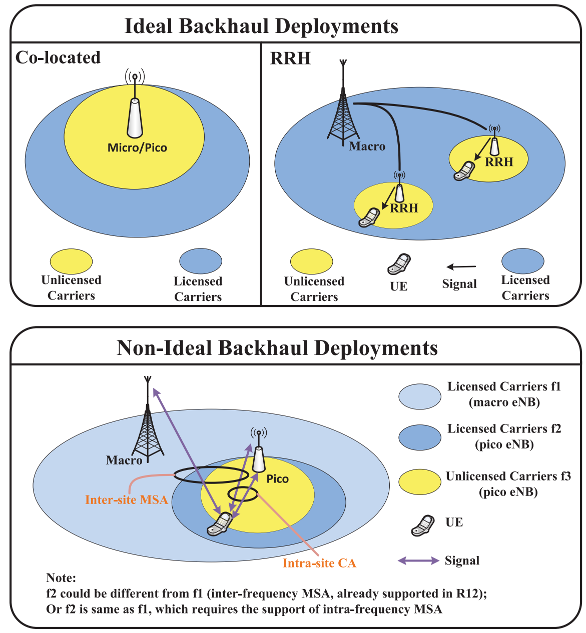

Fig. 10. Ideal/non-ideal backhaul deployments [54].

4) Sparse/Dense SC Deployment: In sparse scenarios, such as hotpot indoor/outdoor places, at most a few SC nodes are sparsely deployed. In dense scenarios, for example in a hypermarket or shopping mall, a large number of SC nodes are densely deployed to support huge traffic. Smooth future extension from small-area dense to large-area dense, or from normal dense to super-dense should be considered particularly.

5) Synchronized/Asynchronous Connection: Both synchronized and asynchronous scenarios should be considered between LTE-LAA and/or Wi-Fi SCs as well as between SCs and Macro cell(s).

6) Spectrum: As to the spectrum factor in classifying scenario deployment, there are some example of spectrum configurations. The first case is when the carrier aggregation appears on the Macro layer with bands X and Y, only band X and Y, or only band X staying on the SC layer. Other two examples show that SCs supporting carrier aggregation bands are co-channel or not co-channel with the Macro layer, respectively.

One potential co-channel deployment scenario is dense outdoor co-channel SCs deployment, considering low mobility users and non-ideal backhaul.

7) Traffic: In an SC deployment, it is likely that the traffic will vary greatly since the number of users per SC node is typically not large due to the small coverage. It is also likely that the user distribution is very fluctuating among the SC nodes.

TABLE VIII
5 GHz SUB-BANDS FOR INDOOR/OUTDOOR ENVIRONMENT IN SOME COUNTRIES

Sub-bands	5.15-5.25 GHz	5.25-5.35 GHz	5.47-5.725 GHz	5.725-5.85 GHz
US/Canada	Indoor/Outdoor	Indoor/Outdoor	Indoor/Outdoor	Indoor/Outdoor
EU	Indoor	Indoor/Outdoor	Indoor/Outdoor	N/A
Korea	Indoor	Indoor/Outdoor	Indoor/Outdoor	Indoor/Outdoor
Japan	Indoor	Indoor	Indoor/Outdoor	N/A
China	Indoor	Indoor	N/A	Indoor/Outdoor
Australia	Indoor	Indoor/Outdoor	Indoor/Outdoor	Indoor/Outdoor
India	Indoor	Indoor	N/A	Indoor/Outdoor

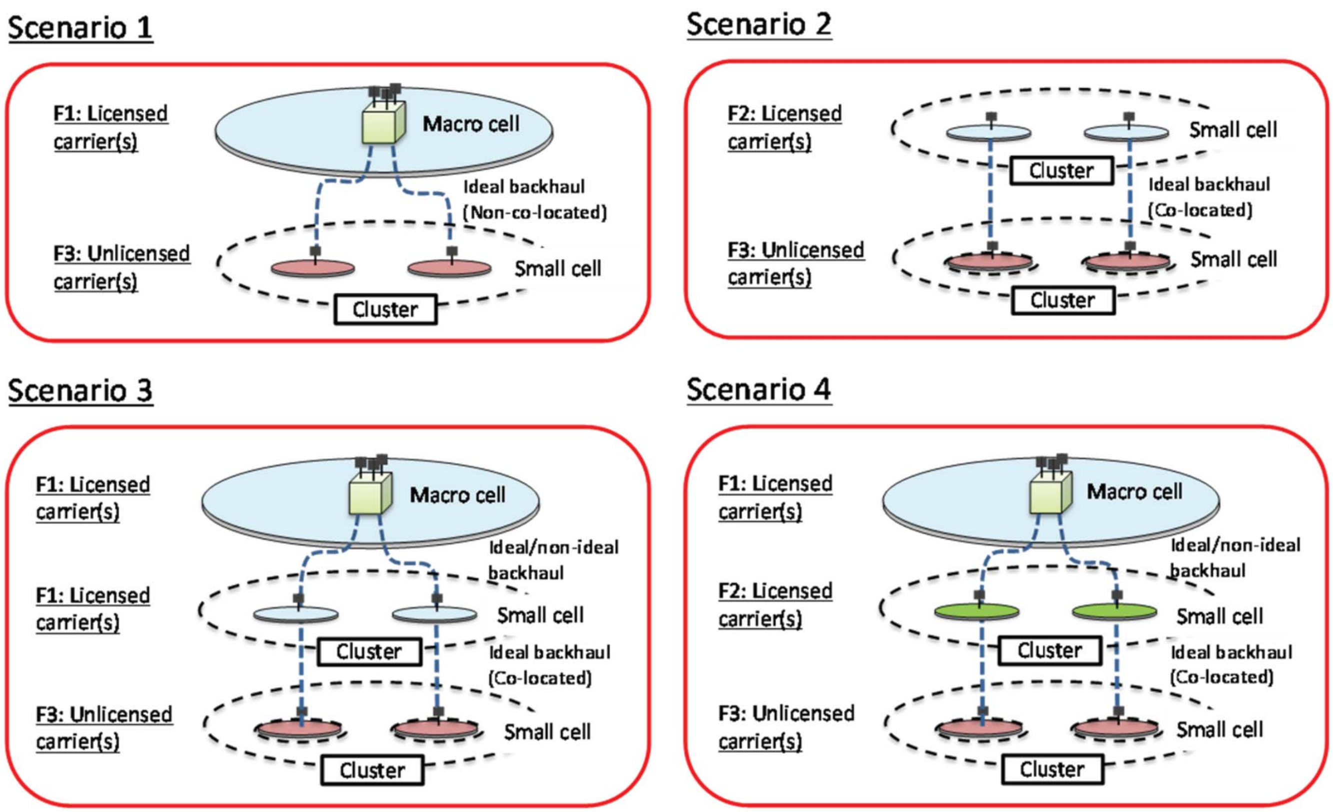

Fig. 11. Four LTE-LAA deployment scenarios designed by 3GPP [72]: a) scenario 1: carrier aggregation between licensed macro cell (F1) and unlicensed SC (F3); b) scenario 2: carrier aggregation between licensed SC (F2) and unlicensed SC (F3) without macro cell coverage; 3) scenario 3: licensed macro cell and SC (F1), with carrier aggregation between licensed SC (F1) and unlicensed SC (F3); 4) scenario 4: carrier aggregation between licensed macro cell (F1), licensed SC (F2) and unlicensed SC (F3) if there is ideal backhaul among macro cell and SC.

The traffic is also expected to be highly asymmetrical, either DL or UL centric one. It should also be noted that traffic load distribution in the time-domain and spatial-domain could be uniform or non-uniform. Each case may correspond to a different scenario.

8) Backward Compatibility: Backward compatibility, i.e., the possibility for legacy (pre-Release 12) users to access an SC node/carrier, will be taken into account for SC deployments. The introduction of non-backwards compatible features should be justified by sufficient gains. In another word, backward compatibility will be an important factor for distinguishing scenarios of deployment if the signal to/from an SC node is not strong to some extent.

B. Representative Deployment Scenarios

1) LTE-LAA Deployment Scenarios Designed by 3GPP: In an SC deployment, multiple scenarios are possible. The scenarios that 3GPP TR 36.889 envisages are shown in Fig. 11, and all include an LTE-LAA SC [72].

In the first scenario, the PCell is the Macro cell, and the LTE-LAA SC is not co-located, but linked to the Macro cell with ideal backhaul. In the other three scenarios, the LTE unlicensed cell is always co-located with a licensed SC, with the SC or the Macro cell acting as the primary carrier. The second scenario is most likely used in indoor environments. The choice of deployment scenario depends on the operators' strategy for SCs and the availability of ideal backhaul.

By consolidating scene classification mentioned in the previous subsection, we concentrate on the following three representative scenarios of LTE-LAA and/or Wi-Fi deployment.

2) Office or CBD Buildings: A potential traffic offloading indoor environment is a multi-floor and multi-room office or Central Business District (CBD) building, where Wi-Fi APs and/or LTE-LAA BSs are set up for indoor coverage only.

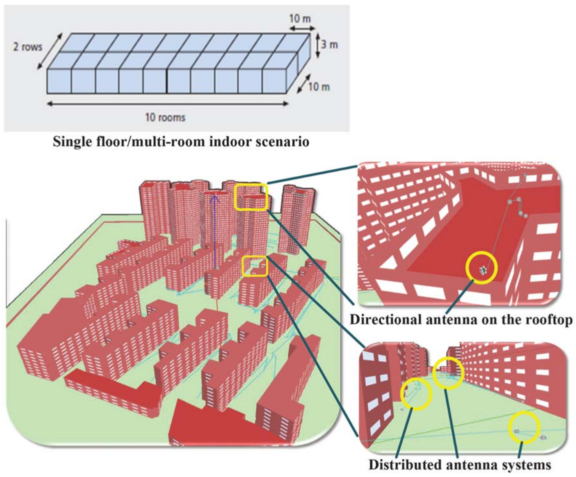

Fig. 12. Office or CBD buildings.

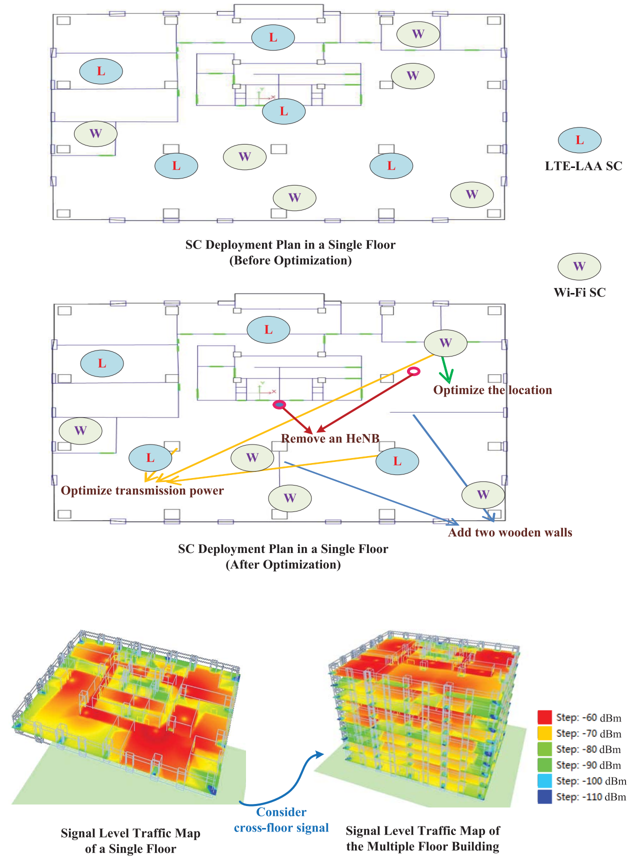

Fig. 13. Scenario-oriented coexistence design for a realistic scenario.

In each floor, a single floor/multi-room indoor scenario, adopted by both 3GPP and IEEE as a realistic scenario to represent residential and small office uncoordinated deployments, can be used for reference as illustrated in Fig. 12 [70]. Each floor consists of 2 rows of 10 rooms, each measuring 10m × 10m × 3m. The cross-floor signal needs to be calculated as well. Whether overlaid Macro cell(s) should be considered is decided by the Macro cell transmission power and features of the building structure, e.g., transmission loss condition of the external wall of building. As shown in Fig. 12, the outdoor coverage is ensured by setting up distributed antenna systems on the ground and directional antennas on the rooftop to cover high floors [96]–[98].

3) Public Establishments: Wi-Fi and/or LTE-LAA hotspots may be found in public establishments such as park, garden and coffee shops in many developed urban areas. In this situation, clustered Wi-Fi APs and LTE-LAA STAs are set up for outdoor coverage with overlaid Macro cell(s). All cells are distributed within a cluster in each Macro area. For closely located cells of different operators, additional minimum distance requirement is needed [99].

4) High Capacity Venues: High capacity venues refer to those scenarios with high dense users. In this case, with overlaid Macro cell(s), Wi-Fi APs are set up for indoor coverage, while LTE-LAA BSs are set up for indoor coverage. The stadium and train station are two typical examples of high capacity venues. Since UEs under those occasions are non-uniformly distributed, it is necessary to design the deployment of LTE-LAA STAs and Wi-Fi APs carefully to guarantee users coverage.

C. An Example of Scenario-Oriented Coexistence Design With Representative Performance Evaluation Metrics and Scenarios

In this subsection we introduce a scenario-oriented decision-making procedure for the coexistence issue.

1) Scenario-Oriented Coexistence Design: A prerequisite issue is whether or not the coexistence of the two technologies in the same unlicensed band is necessarily required. As far as the two aspects of this option are concerned, if the coexistence is inevitable, relevant coexistence mechanisms and parameters should be determined based on the specific scenario so as to settle the coexistence down. On the contrary, if there is no coexistence requirement, in view of the fact that LTE-LAA and Wi-Fi have their own benefits respectively, a question which technology should be chosen for the wireless communication also depends on various scenarios. That is to say, it is the particular scenario that makes sense while operators are considering how to deploy different technologies in 5 GHz UNII band no matter whether to take coexistence issue into account. In the very beginning of consideration for scenario-oriented coexistence, operators should determine whether the coexistence is certainly an uncontroversial choice. If the answer is 'NO', the feature of current deploying scenario can help choose either LTE-LAA or Wi-Fi. If operators are facing an answer of 'YES', they can also optimize coexistence mechanisms and parameters according to the communication traffic map of actual scenarios. For the convenience of understanding towards this kind of practical coexistence design, Fig. 13 is introduced to show a multi-floor and multi-room building with no Macro coverage, consisting of two sketches demonstrating the SC deployment plan in a single floor before and after optimization, respectively, as well as signal level traffic maps for both of a single floor and a multiple floor building.

Particularly, an analysis on the local communication traffic map is the essence of performance evaluation throughout

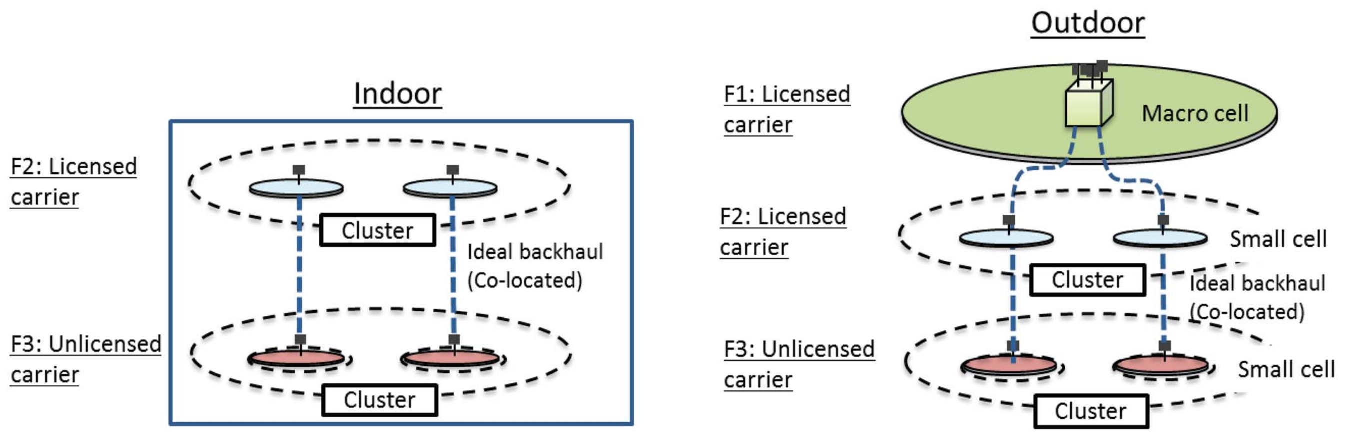

Fig. 14. Two performance evaluation scenarios designed by 3GPP [72]: a) indoor scenario; b outdoor scenario, where the licensed carriers for the SC and macro cell are different.

the whole coexistence design process. In the example shown in Fig. 13, indoor co-floor and cross floor signal can be predicted with the help of an algorithm of environment modeling combined with radio propagation modeling. By executing the simulation and utilizing the prediction results of signal transmission, which could be calibrated with measurement data to ensure accuracy, the performance of LTE-LAA and/or Wi-Fi in this scenario can be evaluated correctly to a great extent.

To observe the details, for example, the simulation baseline or the first case is the one where all APs within a hotspot comply with Wi-Fi 802.11ac. The second case is a mixture of two groups with a specific coexistence mechanism, where one group is Wi-Fi and the other is LTE-LAA. In the third case, all Wi-Fi APs in the baseline are replaced by LTE-LAA nodes. The performance comparison of the two technologies among those three cases can help the operator determine whether considering the coexistence issue is the best choice before making further efforts. If the answer is 'NO', key factors of performance difference between LTE and Wi-Fi discussed before can assist the operator in choosing his/her favorite technology, i.e., either Wi-Fi or LTE-LAA. If the answer is in the affirmative, the performance of the whole system can be further optimized by adjusting one or more simulation parameters. The shadow of LTE-LAA interference on Wi-Fi can be shifted by several elements defined by [100]. For instance, it is concluded that LTE-LAA with smaller bandwidths may cause severe performance degradation of Wi-Fi. There is another fact that blocking LOS between LTE-LAA and Wi-Fi links can effectively decrease the impact of interference. Special care is thus required while simulating the coexistence channel model and designing mechanisms for channel/bandwidth selection. Moreover, multiple optimization methods shown in Fig. 13, e.g., adjusting locations of SCs, optimizing the transmission power of some HeNBs to reduce interference, adding walls for better interference isolation and removing unnecessarily deployed SCs, etc., can be used to improve the performance of indoor cells [101].

2) Representative Performance Evaluation Scenarios: In this section, both indoor and outdoor scenarios for coexistence evaluations designed by 3GPP are discussed [72]. As shown in Fig. 14, the licensed carrier for the SCs is different with that for Macro cell in the outdoor scenario. Performance of user(s) attached to the Macro layer is not evaluated. More than one carrier can be considered for the unlicensed carrier. It should be noted that the evaluation scenarios designed by 3GPP do not restrict the design of target scenario for LTE-LAA. In the LTE and Wi-Fi coexistence case, in the first step, performance metrics for two Wi-Fi networks coexisting in a given evaluation scenario need to be evaluated and recorded. Then, in the second step, Wi-Fi is replaced with LTE-LAA for the group of eNBs and users served by one of the Wi-Fi operators. Performance metrics of the Wi-Fi network coexisting with the LTE-LAA network need to be evaluated and recorded too. A comparison of the performance metrics between two steps can be used to evaluate coexistence between LAA and Wi-Fi in an unlicensed band.

3) Recommended Performance Evaluation Metrics: The performance should be judged from different angles [102]. The most common criterion is the user throughput, which refers to the number of packets received for each LTE/Wi-Fi node during whole simulation time. The transmission success rate is also worth considering. The Signal to Interference plus Noise Ratio (SINR), Wi-Fi listen mode, as well as Wi-Fi transmit/receive mode also make sense. More researches are urgently needed on summarizing assessment techniques. The following typical metrics recommended by the community may be considered for coexistence performance evaluation in testing or simulation [72], [76], [79]:

a) *SINR:* The SINR of user m associated to SC x is appropriately written as:

$$SINR_m^k = \frac{P^{WiFi}\left(L_{m,x}\right)^{-1}}{N_0 + \sum_{y\epsilon A_y^j} P^{WiFi}\left(L_{m,y}\right)^{-1} + \sum_{y\epsilon B_y^j} P^{LAA}\left(L_{m,y}\right)^{-1}}, \quad (1)$$

where $A_y^j = A^j \setminus A_x^j$, where A^j is the set of all Wi-Fi SCs transmitting on channel j and A_x^j is the contention domain of SC x. Similarly, $B_y^j = B^j \setminus B_x^j$, where B^j is the set of all LTE-LAA SCs transmitting on channel j and B_x^j is the contention domain of SC x. N_0 is the noise power. k can be LTE-LAA or Wi-Fi.

b) *User throughput:* It refers to the data rate over the time from the packet arrival to delivery during the interval divided by the interval period. The number of served bits of an unfinished file by the end of the simulation is divided by the served time. In actual operation, user throughput is the average of all its file throughputs. The interval periods recommended by [79] is to be at least 500 ms. We could further calculate the throughput of user m associated with SC x as:

$$R_m^k = \frac{1}{\left|A_x^j\right| + \left|B_x^j\right|}\rho_k\left(SINR_m^k\right), \tag{2}$$

where ρ_k is the auto-rate function specified in the IEEE 802.11ac standard.

c) *Latency:* Latency is defined as a time interval between time one and two, i.e., when a packet arrives at the entry point on the source until it is successfully delivered at the exit point on the destination. Latency is measured at the top of the MAC for simulation, but can be measured higher in the network stack for device studies. It is recommended that the number of users with the latency greater than 50 ms should be reported [72]. Due to practical limitations, it may only be possible to measure packet-by-packet latency for a few seconds. In such cases, the latency metric shall be measured for the longest duration.

d) *Average buffer occupancy:* Packet arrival rate for the measured buffer occupancy of the non-replaced Wi-Fi network in Wi-Fi and Wi-Fi coexistence scenario is used as the packet arrival rate in Wi-Fi and LTE-LAA coexistence evaluations.

e) *Loading on unlicensed layer:* Let $q_{m,x,h,t}$ be the size of the queue for the user m connected to the SC x for the operator h (h=1 or 2) at time t. Loading over the unlicensed layer per SC can be defined as:

$$L_{x,h} = \frac{\sum_t 1\left(\sum_{m\epsilon\Omega} q_{m,x,h,t} > 0\right)}{T}, \tag{3}$$

where 1(.) is the indicator function, T refers to the total simulation time, and Ω is the set of users within 5 GHz coverage.

f) *Resource utilization on unlicensed layer:* Resource utilization can be defined as:

$$U_{x,h} = \frac{\sum_t 1\left(P_{x,h,t}\right)}{T}, \tag{4}$$

where $P_{x,h,t} = 1$ if SC x of operator h is transmitting at time t over unlicensed layer (i.e., to one of the users in Ω).

g) *Packet loss:* A lost packet is defined as a packet that entered the source for transmission but was never received by the destination. The packet loss metric is calculated as a percentage of lost packets to the total packets attempted.

There are some other important metrics not captured in the current simulation and test, as well as proposed test plan, e.g., power save signalling loss and deferral. How well LTE-LAA and Wi-Fi play together in the real world will likely continue to be a point of industry contention.

4) Some Key Questions to Direct Future Researches in Scenario-Oriented Coexistence Issue: A cooperation mechanism together with coexistence rather than a coexistence mechanism alone might become an option in future studies. Generally speaking, our suggestion is to firstly optimize the system performance based on the communication traffic map. Then, operators or even users can choose the best plan for the deployment of LTE-LAA and/or Wi-Fi in a specific scenario.

On the whole, as to the challenge of coexistence issues, a series of questions as follows could be summarized to direct future researches in this field.

1) For the purpose of performance maintenance, in which deployment scenario should either LTE-LAA or even Wi-Fi be used alone in 5 GHz UNII band without considering coexistence issue?
2) Otherwise, if coexistence is certainly needed, is it possible for the operator or the user to define the coexistence mechanisms and parameters based on the local communication traffic map?
3) On the other hand, is coexistence combined with cooperation mechanisms rather than coexistence alone a better choice to handle the interference among those different RANs?

VI. Challenges and Further Research Directions

A. Challenges

To meet the coexistence challenges proposed in Section III-D, the community has proposed several coexistence mechanisms for both markets with and without LBT requirement. However, as discussed in above sections, such a kind of coexistence is not going smoothly thus far. We summarize the key challenges related to the LTE-LAA and Wi-Fi coexistence as follows:

a) *Disputes over the effectiveness on current coexistence mechanisms are still the hot topic of the community:* As discussed in Section IV-D, both duty-cycling and LTE-LAA with LBT are designed for specific markets. What's more, as stated in Sections IV-A and IV-D, both mechanisms have their own weaknesses, and dispute remains over whether these mechanisms are valid in some specific scenarios. An agreement among the community is needed on one or more acceptable coexistence mechanisms.

b) *The lack of documented agreement on a definition of fairness is a big problem:* As stated in Section III-D, there exist different kinds of definition of fairness. The situation that Wi-Fi stakeholders tend to accept that fairness criteria means LTE-LAA should not impact Wi-Fi more enormous than another Wi-Fi network. Some 3GPP members believe that fair access means that LTE-LAA BS and IEEE 802.11 clients should have half of the bandwidth respectively. An agreement is required on the definition of fairness or a mechanism that achieves fairness.

c) *It is still too early to determine whether LTE-LAA is successful:* LTE-LAA is just one of a number of spectrum-sharing methods being used now with others in development or in test trials. As stated in Section IV-D, the disagreement among different members in the community shows that there is no unified test platform. Furthermore, more researches concerning coexistence optimization are required. For example, new objective functions for optimizations problem formulations to guarantee the fair coexistence of LTE-LAA and Wi-Fi are needed. The attributes of the CR to optimize LTE-LAA in 5 GHz are also required. What's more, more complex tests on fairness, especially those based on a range of realistic usage scenarios are urgently needed. That means, before drawing any conclusions, the community should first complete simulations representing more realistic usage scenarios.

d) *It lies in the features of specific scenarios that decide the coexistence is necessary or unnecessary:* That is to say, if it is not worthwhile for operators to deploy LTE-LAA from the perspective of various performance metrics, the coexistence is not necessary accordingly. From the view of market and technology, both LTE-LAA and Wi-Fi have their own benefits and cannot be replaced by each other. In this case, the choice of Wi-Fi or LTE-LAA is also related to the experience of operators and even financial and other factors.

In light of the aforementioned challenges, we put forward several alternatives to LTE-LAA, or solutions complementary to it in the following subsections.

B. LTE in Other Bands

1) LTE in Other Unlicensed Bands: 3GPP has decided to focus initially on the 5 GHz band, but some other unlicensed bands are still available. For example, LTE-LAA could easily expand to 2.4 GHz, though this band is already congested and hence unlikely to protect its LTE-LAA investment currently. The 60 GHz band is another possible target, but the range is too limited to be used in the enterprise or in public venues [53].

2) LTE in Other Licensed Bands: The main purpose of aggregating LTE to the unlicensed bands is that it gives operators access to a new band. Meanwhile, there are other licensed bands available that can be used to add capacity to cellular networks. The 3.5 GHz band, for example, is an attractive option. Due to its short coverage radius, the 3.5 GHz band is not suited for Macro deployments, but it works well as an under-layer for SCs that, unlike co-channel deployments, does not create interference with the Macro layers [53].

C. Wi-Fi Offloading

Standards in which the Wi-Fi deals with authentication have been under consideration, such that the offloading from LTE to Wi-Fi will happen seemingly. Indeed, alongside LTE-LAA, recent work by the 3GPP on offloading to the WLAN is also being discussed. The inherent constraints of cellular networks, particularly due to cross-tier and co-tier interference, motivate offloading some of the traffic to the Wi-Fi band, so as to alleviate the interference and ease congestion. 3GPP has defined several Wi-Fi offloading mechanisms which rely on the connection between the LTE and Wi-Fi.

1) LTE and Wi-Fi Integration: With carrier Wi-Fi, Wi-Fi infrastructure can be utilized. Because with carrier Wi-Fi, LTE and Wi-Fi can be integrated in the core, operators can present a consistent set of policy and services. However, due to the different mobility, authentication, security, and management between LTE and Wi-Fi, there is still work ahead before achieving full integration.

2) LWA as an Alternative: 3GPP has approved a Release 13 work item on LWA according to 3GPP RP-151022, where an eNB schedules packets to be served on LTE and Wi-Fi radio links. However, due to time constraints, a number of proposed enhancements were left out.

The basic idea of LWA is that mobile operators use Wi-Fi for access, with Wi-Fi transmission integrated in the cellular RAN. The RAN manages the traffic, and all signalling goes through LTE in a licensed channel.

Complementary to carrier Wi-Fi and LTE-LAA, LWA enables operators to integrate Wi-Fi. Moreover, LWA has several advantages. First, unlike LTE-LAA, it requires little intervention in existing networks and in devices since the WLAN radio link effectively becomes part of the E-UTRAN. Furthermore, because it uses ubiquitous Wi-Fi and LTE wireless interfaces, it can become commercially available in a short term. More works are required to quantify the performance comparison between LWA and LTE-LAA, especially if the LBT implementation is considered [53].

Additionally, Wi-Fi specifications continue to evolve. IEEE 802.11 is being adjusted towards 802.11ax which aims at increasing spectral efficiency in 2.4 and 5 GHz bands, particularly in dense deployments with a theoretical peak throughput up to 9.6 Gbps and 1.6 Gbps under more realistic conditions. In the millimetre wave band of 60 GHz, 802.11ad is a ratified amendment to 802.11 that defines a new physical layer for 802.11 networks and can offer up to 7 Gbps throughputs. 802.11ay is in the process of enhancing 802.11ad and aims at improving mobility, range and providing data rates of at least 20 Gbps. Even though LWA framework has been designed largely agnostic to 802.11 technologies, such increased data rates may require additional optimizations [56].

Currently Release 13 assumes no IEEE 802.11 impact and requires little coordination between 3GPP and IEEE. In Release 14, proactive cooperation and coordination between 3GPP and IEEE may allow LWA and IEEE 802.11 evolution to be more harmonious, further increasing the benefits of these technologies.

D. RAN Evolution of LTE-LAA in Release 13 and 14

Release 13 was completed in March 2016, although some features might ask for an extended period for completion. Use of unlicensed spectrum is increasingly considered by cellular operators as a complementary tool to argument their service offloading and solutions. Efficient use of unlicensed spectrum as a complement to licensed spectrum has the potential to bring great value to service providers, and, ultimately, to the wireless industry as a whole. Given the widespread deployment and usage of other technologies in unlicensed spectrum for wireless communications, it is necessary that LTE has to coexist with existing and future uses of unlicensed spectrum. In the most recent work within Release 13, more investigations continue to enter into LTE-LAA, with the start of specification work on LTE-LAA DL operation [25].

The 3GPP RAN group has also started working on the evolution of LTE specifications in Release 14. Within Release 13, 3GPP only defined DL design for LTE to utilize the unlicensed spectrum. To leverage the full benefits of LTE operation in unlicensed spectrum, it is of utmost importance to define a complete UL access scheme in addition to the already defined DL access scheme. Release 14 will further investigate enhanced LAA, or eLAA as the next iteration to enable the aggregation both in the DL and the UL.

VII. Conclusion

For the top QoS of LTE-LAA and/or Wi-Fi in 5 GHz unlicensed band, we overviewed several key coexistence related features of the two technologies, and some key factors of performance difference between LTE and Wi-Fi. As a result, some valuable lessons have been learnt from LTE and Wi-Fi MAC comparison for the guideline of the choice of LTE-LAA and Wi-Fi. Furthermore, in Section IV, to reach a better understanding of current consideration about the coexistence of LTE-LAA and Wi-Fi in the field of wireless communication and to evaluate the associated influence on wireless services, we first summarized the recent related works to present a stage picture of the research in the community. Coexistence mechanisms in both markets where LBT backoff mechanism is required or not have all been investigated. Meaningful lessons have been derived from different coexistence mechanisms comparison and CR, along with some important recommendations for ensuring fairness. Moreover, after summarizing eight primary influential factors for the classification of SC scenarios and concentrating on four representative scenarios of LTE-LAA and/or Wi-Fi deployment, we analyzed the whole procedure of design for an example scenario-oriented coexistence design by focusing on various coexistence schemes for different access applications. Accordingly, we further recommended performance evaluation scenarios and metrics. Besides, key challenges and research trends have all been put forward as our guidelines.

The contribution of this survey mainly lies in a scenario-oriented decision-making procedure for the coexistence target, and recommendations related to LTE-LAA and Wi-Fi coexistence. We expect that our work could attract much more attention from the academia and industry to promote the corresponding research activities, especially future studies on cooperation-assisted coexistence mechanisms, and might provide helpful indications for deployment of LTE-LAA and/or Wi-Fi on 5 GHz UNII band.

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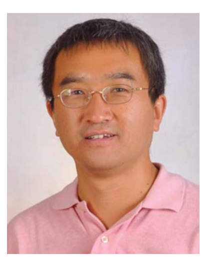

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