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Resource Management in LTE-U Systems: Past, Present, and Future

RUI LIU[1], QIMEI CHEN[2] (Member, IEEE), GUANDING YU[1] (Senior Member, IEEE), GEOFFREY YE LI[3] (Fellow, IEEE), AND ZHI DING[4] (Fellow, IEEE)

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[1]College of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027, China
[2]School of Electronic Information, Wuhan University, Wuhan 430072, China, and also with the National Mobile Communications Research Laboratory, Southeast University, Nanjing 211189, China
[3]School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA
[4]Department of Electrical and Computer Engineering, University of California, Davis, CA 95616 USA

CORRESPONDING AUTHOR: QIMEI CHEN (e-mail: chenqimei@whu.edu.cn).

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ABSTRACT With the tremendous growth in mobile data traffic, wireless cellular networks are facing a rigorous challenge to increase network capacity. Despite that many advanced technologies are used, the shortage of spectrum resource is still the main bottleneck for capacity enhancement. To address the challenge, the cellular networks have been motivated to seek for more fruitful radio spectra. Amongst many others, the unlicensed 5 GHz spectrum is a promising candidate due to its low channel attenuation, large available bandwidth, and easy to utilize. Therefore, the innovative technology of long-term evolution (LTE) using the unlicensed spectrum, known as LTE-Unlicensed (LTE-U), has been widely investigated as a promising means to increase the data rate of cellular networks. The unique characteristics of the unlicensed spectrum bring new challenges to resource management in the LTE-U system. During the last few years, there have been a lot of resource management designs for the newly-born but vigorous LTE-U technologies. This paper provides a comprehensive overview of the state-of-the-art resource management scenarios in LTE-U systems, including single small cell base station (SBS), multiple SBSs, device-to-device (D2D) networks, vehicular networks, and unmanned aerial vehicle (UAV) systems. The future research issues of resource management in LTE-U for 5G are also outlined.

INDEX TERMS 5G, LTE-Unlicensed, resource management, scheduling.

I. INTRODUCTION

WIRELESS communications have witnessed an unprecedented proliferation in both the number of mobile terminals and the traffic demand for various multimedia applications. Compared to 2015, global mobile data traffic is forecasted to grow 727% by 2020 [1]. The huge gap between present capabilities and the forecasted demand has prompted academic and industrial communities to seek advanced technologies for improving network capacity. Enhanced long-term evolution (LTE), also known as LTE-Advanced (LTE-A) [2], has been developed by the third generation partnership project (3GPP) to provide significantly higher data rates and better user experience through many cutting-edge technologies, such as massive multiple-input multiple-output (MIMO) [3], [4], carrier aggregation (CA) [5], full-duplex (FD) communications [6], and device-to-device (D2D) communications [7], [8]. The seamless convergence of such technologies within the same architecture has allowed the traditional licensed spectrum to meet current network performance demands in addition to promoting a high spectral efficiency of the current wireless cellular network. On the flip side, it leaves little margin for further capacity improvement. However, the limited licensed spectrum is deplorably insufficient as well as diminishing. Such a looming spectrum crunch becomes the pivotal constraint on further capacity enhancement.

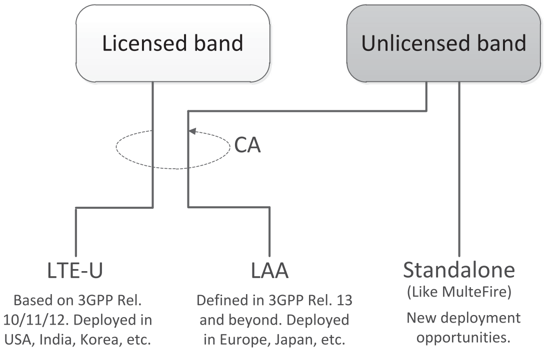

FIGURE 1. The relationship between LTE-U, LAA, and MulteFire.

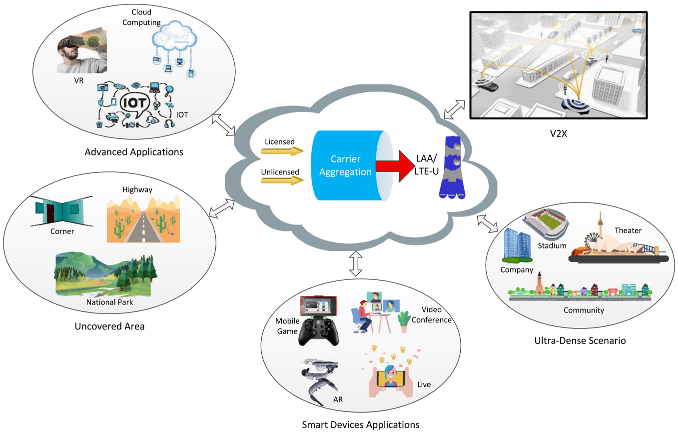

FIGURE 2. Applications of the LTE-U technology.

Cellular networks have been motivated to utilize the abundant unlicensed spectrum for capacity enhancement. The idea of extending LTE to the unlicensed spectrum, also known as LTE in unlicensed spectrum (LTE-U), has been widely investigated recently. The LTE-U Forum has been formed to push forward various deployments based on 3GPP Release 10/11/12 as demonstrated in Fig. 1. Meanwhile, as another version of LTE-U, the licensed-assisted access (LAA) using LTE has been also standardized in the 3GPP Releases 13, 14, and beyond [9]–[25]. The above two techniques aggregate unlicensed spectrum with an anchor in licensed spectrum. The MulteFire, on the other hand, operates the LTE-based technology solely in unlicensed spectrum and provides a more flexible deployment scenario for LTE-U [26]. To avoid unnecessary confusion, in this article, we utilize the concept "LTE-U" to cover all technologies that extend 3GPP LTE systems to the unlicensed spectrum.

LTE-U technology brings many advantages for mobile users as compared with traditional wireless local area network (WLAN) technology. Cellular systems are based on centralized media access control (MAC) protocols with scheduling-based channel access, whereas WLAN uses decentralized MAC protocols with contention-based random access. Despite the advantages of flexibility, cost-effectiveness, and self-organization of the WLAN systems, the centralized LTE MAC protocol can achieve various performance gains due to its efficient multi-user transmission scheduling. Therefore, it has been recently proven that the unlicensed spectrum can be utilized more efficiently by LTE technology. From the perspective of the user side, leveraging the existing CA technology, cellular users can access both licensed and unlicensed spectra to boost their data rates. Moreover, through a single evolved packet core (EPC) network that facilitates compatibility among different types of wireless networks, the data flow between licensed and unlicensed spectra can be seamless under a unified LTE network infrastructure. Therefore, the LTE-U technology is especially useful in remote areas that often lake the advantages of LTE network coverage, ultra-dense scenarios, smart devices, future applications, and vehicle to everything networks, as shown in Fig. 2.

Despite the many advantages of LTE-U, it also faces two pivotal technique challenges for practical deployment. The first is the coexistence with WiFi networks. LTE is designed as an exclusive system to avoid uncontrolled interference on the same frequency band while WiFi systems manage the spectrum resources in a competitive fashion via distributed coordination function (DCF). Therefore, LTE-U will cause significant performance degradation on WiFi users without efficient coexistence mechanisms. The second challenge is resource management for LTE-U systems, which plays an important role in determining system performance. The addition of unlicensed spectrum makes the current results of traditional LTE systems inappropriate for LTE-U systems, where several new research issues, such as the balance between the LTE-U and WiFi networks, and the spectrum sharing among operators on unlicensed spectrum, should be carefully considered. In this paper, we focus on the resource management issue in different LTE-U scenarios.

Recently, there exists several review articles on LTE-U as summarized in Table 1. An overview of LTE-U in [38] covers regulations, principles, typical deployment scenarios, and several key challenging issues. An outlook on LTE-U in 3GPP Release 14 in [40] is mainly about the physical layer techniques. An overview in [29] mainly focuses on the changes in the downlink physical channels for the new LTE-U features, such as discontinuous transmission (DTX) and listen-before-talk (LBT). The hybrid automatic repeat request (HARQ) feedback procedures, scheduling algorithms, and radio resource management (RRM) mechanisms in LTE-U systems are also discussed in [29]. The enabling features for LTE and WiFi coexistence are discussed in [28], where further directions for coexistence mechanisms are presented. The challenges for the coexistence of LTE-U and WiFi are addressed in [41] and [42], where novel LBT-based coexistence mechanisms are also proposed. On the other hand, there have been some surveys on LTE-U technology from different perspectives. A comprehensive survey on the coexistence of LTE-U and WiFi with corresponding deployment scenarios is provided in [31]. The physical layer design principles of LTE-U are analyzed in [32], where a baseline cellular framework is provided to illustrate how the traditional cellular systems can

TABLE 1. Summary of the Overviews and Surveys of LTE-U

Articles	Focus	Description
[27]	Network coexistence	An overview of key design aspects of LTE-U LBT 1. LAA-LBT energy detection energy; 2. The period that LTE-U transmitter freezes updating the backoff counter; 3. Three approaches of LBT for multicarrier LTE-U; 4. Key aspects of LTE-U uplink design.
[28]	Network coexistence	A brief overview of coexistence mechanisms and future research directions 1. Flexible spectrum access enabled by LTE/WiFi; 2. Channel selection enabled by WiFi; 3. Almost blank subframes enabled by LTE; 4. Transmit power control enabled by LTE.
[29]	Network coexistence	An overview of design agreements for LTE-U 1. Baseline LBT framework for a single carrier; 2. Downlink LTE-U physical layer architecture; 3. The scope of additional enhancements beyond LTE Release 13.
[30]	Network coexistence	An overview of coexistence mechanisms and standards 1. The review and comparison of dynamic carrier selection, CSAT, blank subframes, frame/load-based LBT, and transmit power control; 2. The comparison of LTE-U, LAA, eLAA, and MulteFire.
[31]	Network coexistence	A comprehensive survey on LTE-LAA and Wi-Fi coexistence 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.
[32]	Physical layer	A comprehensive analysis on the physical layer design principles of LTE-U 1. Review of the regulatory requirements on unlicensed spectrum; 2. Analysis of the key factors for the implementations of LTE-U; 3. Description of LTE-U and LAA.
[33], [34]	Networking	Review and technical analysis of different networking approaches of LTE-U.
[35]	Traffic steering	An overview of traffic steering in LTE-U 1. Spectrum-based cell zooming; 2. Unlicensed D2D assisted traffic steering; 3. Spectrum-sharing based traffic steering.
[36]	Overall description	An overview of LTE Release 13 LTE-U LBT technology 1. Scenarios and use cases; 2. Key technical features of the LTE-U in Release 13; 3. LTE enhancements to support LTE-U;
[37]	Overall description	An overview of various technical issues 1. Fundamental access issues in LTE-U operations; 2. Critical enabling techniques; 3. Coexistence considerations; 4. Open research opportunities.
[38]	Overall description	An overview of LTE-U from both operator and user perspectives 1. Design regulations and principles; 2. Deployment scenarios; 3. Potential benefits from LTE-U; 4. Intra-operator traffic offloading and inter-operator spectrum sharing.
[39]	Overall description	An overview of the state-of-the-art research on LTE-U 1. Regulation and standardization; 2. Design issues from the technical and business points of view; 3. Deployment scenarios and technical solutions with analysis.

be mutated to coexist with other systems when operating on a different type of spectrum. To the best of our knowledge, this is the first to provide a comprehensive survey on resource management in different scenarios of LTE-U systems.

The rest of this article is organized as follows. In Section II, we briefly introduce basic technologies of LTE-U. In Sections III and IV, we discuss resource management in single SBS scenario and multiple SBSs scenario, respectively. We address LTE-U related scenarios in Section V. In Section VI, we identify open research directions of LTE-U for 5 G design before conclusions are drawn in Section VII.

II. FUNDAMENTALS

For a better understanding of resource management in LTE-U systems, basic technologies for LTE-U are briefly introduced in this section, including the LTE-U networking, and the coexistence between LTE-U and WiFi.

A. LTE-U NETWORKING

Transmission on unlicensed spectrum is generally unstable since the nature of being unlicensed makes it hard to guarantee the quality of service (QoS). To ensure the QoS and improve the user experience, the LTE-U transmission should be assisted by the CA technique suggested in 3GPP Release 10 to Release 12 specifications. With the CA technique, a wider virtual bandwidth could be obtained with the aggregation of component carriers in different frequency bands and thus a higher data rate can be achieved.

The aggregation of licensed and unlicensed spectra in LTE-U systems is similar with the first phase of LTE-A CA in commercial scenarios, where a primary component carrier (PCC) and several secondary component carriers (SCCs) are aggregated for transmission. The important control messages, including radio resource control signals and layer 1 signals, should be transmitted on PCC for better QoS provision. The LTE standard has defined nine QoS class identifiers in licensed spectrum for different types of applications, among which the control messages are granted the highest priority. Therefore, the PCC of LTE-U is usually transmitted in the licensed spectrum to guarantee its QoS. In this way, the transmission of control signaling between small cells and users can be ensured whatever the unlicensed channel conditions are.

There have been two operation modes for LTE-U: the supplemental downlink (SDL) mode and the time division duplex (TDD) mode. In the SDL mode, the unlicensed spectrum is only used for downlink transmission since the downlink traffic is generally much heavier than the uplink one. The data-hungry downlink applications, such as file downloading and online video streaming, are suitable to operate in this mode. Under the SDL mode, LTE-U SBSs can perform most of the required operations for reliable communications, including the detection of the unlicensed channel occupancy without the cooperation of users. On the contrary, in the TDD mode, the unlicensed spectrum is used for both downlink and uplink transmissions, which needs extra implementation complexity on the user side to offer scheduling flexibility and resource allocation between downlink and uplink. The TDD mode is appropriate for those applications requiring high uplink rates, such as file transfer protocol (FTP) uploading and real-time video chatting. Besides, MuLTEfire enables LTE users to transmit on the unlicensed spectrum without a licensed anchor channel, and has not been discussed in 3GPP yet.

From the perspective of radio resource management, tremendous benefits can be achieved by LTE-U. As mentioned before, a wider bandwidth could be obtained with the CA, leading to a significant increase in data rate. In addition, LTE-U is more spectra-efficient than WiFi in the unlicensed spectrum for its centralized channel access and multi-user scheduling mechanism. With the user feedback information of the channel qualities, the multi-user transmission can be scheduled by the centralized MAC to achieve multi-user diversity gain. Furthermore, other advanced LTE technologies can also be extended into the unlicensed spectrum, such as D2D communications, FD communications, and massive MIMO transmission, leading to an even higher data rate. Moreover, users in the LTE-U system are operated within a unified network architecture on both licensed and unlicensed spectra.

B. COEXISTENCE BETWEEN LTE-U AND WIFI

Cellular networks are designed on the basis of exclusive spectrum access in general, without sharing spectrum with other networks. However, the unlicensed spectrum can be open-shared by many radio access technologies. For example, unlicensed spectrum needs to be shared with the WiFi network, which typically utilizes the DCF for channel access. In LTE-U systems, the network coexistence becomes much more complicated since LTE and WiFi have totally different channel access protocols and there is no centralized controller to coordinate the spectrum sharing. This subsection mainly focuses on various coexistence mechanisms for LTE-U and WiFi, including dynamic channel selection (DCS), carrier sensing adaptive transmission (CSAT) and listen-before-talk (LBT).

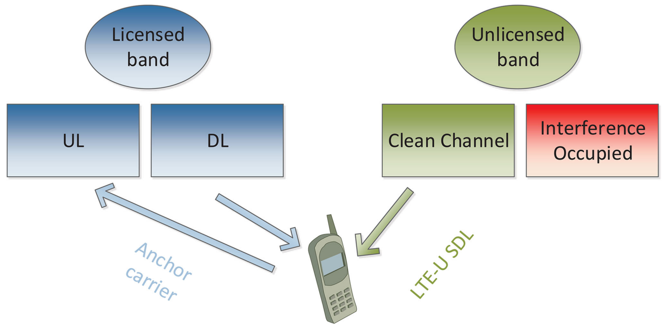

FIGURE 3. **Channel selection for LTE-U SDL transmission.**

1) DYNAMIC CHANNEL SELECTION

Since the 5 GHz band has more than 20 non-overlapping 20 MHz channels, it is expected that the frequency-domain mechanism is the most effective way to avoid the co-channel interference between LTE-U and WiFi networks in light-load scenarios. Based on DCS, before an LTE-U small cell base station (SBS) launches unlicensed transmission, it will first sense the unlicensed band and ascertain the clean channels for transmission. If there is no clean channel, it will choose the least occupied ones. The measurement operations can be performed on the initial power-up stage and the later transmission stage periodically. If interference is detected on the currently occupied channel and there is another unused channel that is sensed available at the same time, the transmission will switch to the new channel via the carrier aggregation procedure within LTE standards. Fig. 3 shows the DCS scheme for LTE-U SDL transmission. Moreover, the DCS mechanism can coordinate with the least congested channel search (LCCS) mechanism in WiFi systems to facilitate the channel selection.

2) CSAT

Clearly, the DCS mechanism can significantly mitigate the interference between LTE-U and WiFi operating on the same unlicensed channel. However, LTE-U SBSs with DCS mechanism have to stop transmission when there is no clean channel available. This greatly affects the effectiveness of this mechanism. Meanwhile, there is a high probability that no clean unlicensed channel will be found when the WiFi networks are densely deployed. In such cases, the LTE-U SBSs can still share the unlicensed channel with the adjacent WiFi APs utilizing duty cycle muting (DCM) mechanism, which enables DTX. The common goal of these mechanisms is to provide a coexistence scheme through time-division multiple access (TDMA), rather than frequency division multiple

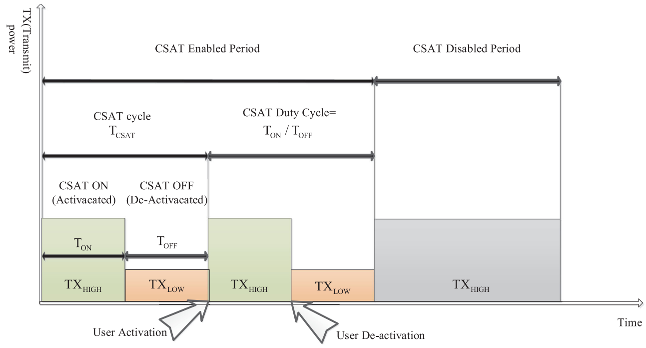

FIGURE 4. CSAT for LTE-U SDL transmission [43].

access (FDMA), as outlined in the DCS mechanism. CSAT is a sort of adaptive muting algorithms, where LTE-U SBS initially and periodically senses the channel for relatively long time periods. CSAT can be configured with little modifications of the current LTE protocols. It thereby has a significant advantage over the LBT mechanism, which requires certain modifications of the LTE protocols. As shown in Fig. 4, CSAT employs an ON and OFF state transition in a single duty cycle [43]. During the ON period, the LTE-U users transmit on the channel with a normal or relatively high power. During the OFF period, the transmission is reduced or even fully disabled in order to yield channel opportunity to the WiFi users. However, the LTE-U SBSs still remain in an active situation during the OFF state. Since WiFi is able to reuse the almost blank subframes (ABSs) ceded by LTE [44], several ABSs may be inserted to provide opportunities for WiFi latency-sensitive applications to go through.

3) LISTEN BEFORE TALK

In a broad sense, LBT is important functionality to avoid a potential co-channel collision as well as the continuous transmission and monopolization of the channel, designed for the wireless communication systems sharing the same channel. The basic idea of LBT is to enable a device to sense its radio environment before starting a transmission. In regions such as Europe and Japan, LBT functionality is mandatory for equipment accessing unlicensed channels where one or more clear channel assessments (CCAs) with least energy detection (ED) should be performed prior to transmitting. If the detected energy is higher than a predefined threshold, the equipment shall defer until the end of the current transmission. Fig. 5 shows the operations of LTE Category 4 recommended by European Telecommunications Standards Institute (ETSI). Once a given channel is sensed busy during the initial CCA, the LTE-U SBS shall generate a random contention window (CW) with a size between $CW_{\min}$ and $CW_{\max}$ and continuously count it down. The LTE-U SBS will not transmit data until the CW size is decremented to zero.

III. RESOURCE MANAGEMENT IN SINGLE SBS SCENARIO

In Fig. 6, we summarize resource management in LTE-U systems from three aspects, i.e., single SBS scenario, multiple SBS scenario, and LTE-U related scenarios. In this section, we focus on resource management in single SBS scenario, including radio access technology (RAT) selection, traffic offloading, and resource allocation, summarized in Table 2.

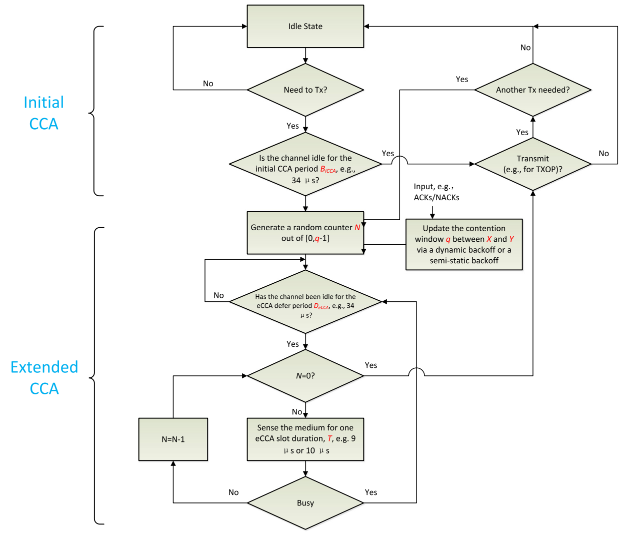

FIGURE 5. LBT Category 4 recommended by in ETSI [36].

A. RAT SELECTION

LTE-U offers a new type of RAT to achieve the gain of multiple radios. The pivotal challenge of multiple radios is to select an appropriate RAT. There are several approaches to select RAT for different scenarios and design goals. For the multi-homing technology in [45], each user can simultaneously access both LTE-U SBS and WiFi access point (AP) to transmit on unlicensed spectrum or just select one of them. In addition, licensed spectrum can be shared by multiple users when they access LTE-U SBS. RAT selection and bandwidth allocation can be jointly performed to maximize the total system throughput, which can be formulated into an NP-hard problem as most resource allocation problems. An effective iterative algorithm has been proposed in [45], in which the inner loop finds the optimal RAT selection with fixed bandwidth allocation through an exhaustive search and outer loops find the optimal bandwidth allocation with known RAT selection with the simplex method. Besides multiple radios operate on the same unlicensed spectrum, the triple-band heterogeneous RAT selection scheme in [46] addresses an LTE licensed network, an LTE-U network, and a millimeter-wave (mmWave) network. Different from the multi-homing technology, which enables simultaneous transmission, the proposed scheme is designed for improving communication experience under different circumstances by accessing only one RAT. In this scheme, users with different requirements of data rates prefer different RATs. Specifically, users requiring gigabit level/megabit level/lower data rate prefer the mmWave/LTE-U/LTE network. A joint RAT selection and bandwidth allocation problem is formulated as

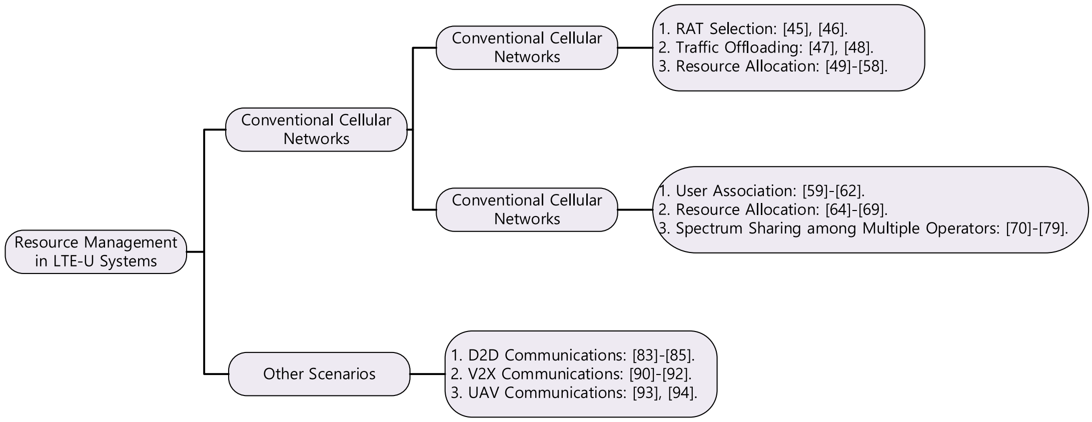

FIGURE 6. **Classification of resource management in LTE-U systems.**

TABLE 2. **Summary of the Literature Focusing on Single SBS Scenario**

Theme	Scenario/Characteristic	Design Objective	Reference	Proposed Solution
RAT selection	Dual-band multi-homing	Maximizing throughput of LTE-U and WiFi	[45]	Propose sufficient conditions for single RAT access and a joint RAT selection and bandwidth allocation algorithm
	Triple-band heterogeneous network	Maximizing sum-rate of total system	[46]	Propose a criterion for RAT selection and a joint RAT selection and bandwidth allocation algorithm
Traffic offloading	Comparison between traffic offloading and resource sharing	Maximizing throughput of SBS	[47]	Propose criteria for selection between traffic offloading and resource sharing and user scheduling algorithms for both scenarios
	Transferring WiFi traffic to LTE-U	Optimizing fairness between LTE-U and WiFi	[48]	Propose a joint user transfer and unlicensed resource allocation algorithm based on NBS
Resource allocation	Unlicensed Resource allocation	Maximizing utility of both WiFi and LTE-U	[49]	Propose a joint subcarrier, time fraction and power allocation algorithm based on a cross-layer optimization framework
		Minimizing interference to WiFi	[50]	Propose a joint channel and occupation time allocation algorithm within 1 ms running time
	Unlicensed resource allocation with spatial reuse	Optimizing fairness between LTE-U and WiFi	[51]	Propose joint user scheduling, DoF allocation, and power allocation algorithms for both lightly-loaded WiFi and overloaded WiFi schemes
	Joint licensed and unlicensed resource allocation with exclusive licensed spectrum	Maximizing system throughput	[52]	Propose a joint bandwidth allocation, time fraction, and power allocation algorithm for hidden node aware systems
		Minimizing interference to WiFi	[53]	Propose an adaptive access scheme with joint bandwidth and power allocation and admission control
		Maximizing EE of LTE-U	[54]	Propose a criterion of whether to utilize unlicensed spectrum and a joint licensed and unlicensed resource block allocation algorithm
	Joint licensed and unlicensed resource allocation with reused licensed spectrum	Maximizing spectrum efficiency of LTE-U	[55]	Propose a joint power allocation and spectrum management algorithm
		Optimizing the fairness between WiFi and LTE-U	[56]	Propose a joint bandwidth and power allocation algorithm based on weighted Tchebycheff method
		Maximizing whole system EE	[57]	Propose a joint power allocation, licensed and unlicensed bandwidth management algorithm based on Dinkelbach method
		Optimizing tradeoff between EE of licensed and unlicensed spectrum	[58]	Propose criteria of whether to utilize licensed and unlicensed spectrum and a resource management algorithm based on weighted Tchebycheff method

maximizing system throughput. With the relaxation of integer RAT selection variables, an iterative method has been proposed to achieve suboptimal solutions by iteratively optimizing the bandwidth allocation and RAT selection. Moreover, with known bandwidth allocation, two criteria for RAT selection are presented. The first one shows that the decisive factor of RAT selection is the overall benefit obtained from allocated bandwidth and related signal-to-noise ratio (SNR). The second one reveals that the decision between LTE-U SBS and mmWave AP is based on the relationship between the gain of low propagation loss from LTE-U SBS and large bandwidth from mmWave AP.

B. TRAFFIC OFFLOADING

Besides directly sharing the unlicensed spectrum to transmit LTE signals, an alternative way is to offload the cellular traffic to WiFi networks. In [47], two fundamental problems have been investigated: traffic offloading or resource sharing, which one is better? Can we further enhance the performance by jointly considering both approaches? From [47], traffic offloading is better only when the number of existing users in WiFi is small. Furthermore, when the number of existing users in WiFi is large enough, traffic offloading is no longer necessary and a hybrid method becomes identical resource sharing.

Since a large number of WiFi devices have the ability to access the cellular networks, a reverse traffic offloading scheme has been proposed in [48], where WiFi tasks are transferred to LTE-U SBS and at the same time, LTE-U SBS accesses unlicensed band as compensation. The benefit of the proposed scheme is two-fold. First, the transferred users from WiFi can be better served since LTE is more spectral efficient than WiFi on unlicensed spectrum due to its centralized scheduling. Second, the supplemental unlicensed resources from WiFi can be utilized to serve existing cellular users. These two benefits build a win-win strategy for LTE-U and WiFi. Three transfer schemes have been proposed according to the availability of channel state information (CSI), namely, random transfer requiring no CSI information, distance-based transfer, and CSI-based transfer, respectively. A joint user transfer and unlicensed resource algorithm has been developed to determine the number of users that need to be transferred as well as the amount of unlicensed resources occupied by LTE-U, which is based on the Nash bargaining solution (NBS).

C. RESOURCE ALLOCATION

We first discuss resource allocation over unlicensed spectrum. With consideration of a coupling relationship between the MAC layer and the physical layer, a generic cross-layer optimization framework has been proposed in [49], where the ratios of channel occupation time of both WiFi and LTE-U networks in the physical layer and the subcarrier power allocation of LTE-U networks in the MAC layer are jointly optimized to maximize the utility of both the WiFi and the LTE-U networks. It has been proved that the cross-layer optimization problem can be decoupled into two independent suboptimization problems solved in the MAC layer and the physical layer, respectively. For the physical layer suboptimization problem, an iterative algorithm has been proposed to find the optimal solution. For the MAC layer suboptimization problem, the closed-form expression of channel occupation time are derived based on the Markov model. In [50], a joint channel assignment and channel occupation time optimization problem has been developed to minimize the interference on WiFi. Since the channel coherence time in 5 GHz is at most 10 ms, which is quite different from the traditional LTE licensed network, the running time of a real-time channel-dependent resource allocation algorithm should be within 1 ms. To this end, the original scheduling problem is decomposed into a large number of independent sub-problems, which can be evaluated in parallel by massive graphics processing unit (GPU) processing cores to determine a near-optimal solution in 1 ms. To further exploit the potential of unlicensed spectrum, MIMO techniques are leveraged in LTE-U networks to achieve the spatial reuse gain in [51], where this scenario, some spatial degrees of freedoms (DoFs) are dedicated for the beamforming of multi-antenna transmission on unlicensed spectrum. Different from conventional cellular networks operating on the licensed spectrum, the implementation of multi-antenna transmission should also consider the inter-RAT interference to the WiFi users besides the intra-RAT interference among cellular users. To coordinate inter-RAT interference, some spatial DoFs are implemented to serve cellular users while others are employed to mitigate inter-RAT interference by applying zero-forcing transmit beamforming (ZFBF). Based on this framework, the optimal number of WiFi users to maximize the WiFi throughput is obtained through performance analysis, which is defined as the boundary between the lightly-loaded WiFi scenario and the overloaded-WiFi scenario. For the lightly-loaded WiFi, a DoF allocation algorithm can balance the throughput of LTE-U and WiFi systems. For the overloaded-WiFi, services of a certain number of WiFi users should be terminated to reduce intra-RAT interference so that the throughput of the LTE-U and the WiFi systems can improve simultaneously with the increasing of DoFs serving cellular users. If a WiFi system is still overloaded even though all DoFs are utilized to serve cellular users, a power allocation algorithm can be used, which increases the transmit power of SBS until the number of the active WiFi users decreases to the optimal number.

Both aforementioned works consider only unlicensed spectrum. It is sometimes important to efficiently integrate the licensed and unlicensed bands to improve the system performance. The joint licensed and unlicensed resource allocation scheme in [52] maximizes system throughput with the consideration of the hidden node problem in WiFi systems. To avoid the impact of hidden nodes, LTE-U SBS should first evaluate the possibility of users affected by hidden nodes before the resource allocation decision making. For the adaptive channel access scheme for LTE-U systems in [53], interference to WiFi system is minimized with the guarantee of LTE-U users' QoS. From [53], in lightly-loaded conditions with a small number of cellular users, the unlicensed spectrum resource is determined to be unnecessary for cellular users if a certain condition is satisfied. In the overloaded condition, with a large number of cellular users, serving all cellular users will damage the QoS of WiFi system and therefore admission control should be used to select the subset of users to serve.

Besides spectrum efficiency and system throughput, energy efficiency (EE) becomes more and more critical for both economic reasons and environmental concerns. Undoubtedly, supplementary unlicensed spectrum can improve system throughput. However, unlicensed bands are generally less energy-efficient than licensed bands since more transmit power may be required to compensate for the lower power amplifier efficiency and larger channel attenuation at the higher carrier frequency. Therefore, a major question for the design of energy-efficient LTE-U networks is when unlicensed bands can be leveraged to improve EE. According to the criterion developed in [54], the EE of LTE-U networks can be improved with a supplement of unlicensed bands only when available licensed resource is not enough. Moreover, a joint licensed and unlicensed resource block allocation algorithm has been developed in [54] to maximize the EE of LTE-U SBS.

It should be noted that SBS is originally designed for enhancing the frequency reuse in licensed spectrum. In some cases, SBS can only share licensed channels with the macrocell base station (MBS), rather than occupy several licensed channels exclusively. In this situation, the joint power allocation and spectrum management method in [55] can maximize the spectrum-efficiency of LTE-U system while guaranteeing the QoS of WiFi. From [55], the spectrum-efficiency of LTE-U systems is still concave even with co-channel interference in unlicensed spectrum. Therefore, optimal solutions can be obtained through simple convex optimization methods. In order to be fair to WiFi users, a tradeoff between the co-channel interference in licensed spectrum and the collision probability caused by SBS users is analyzed to jointly consider the performance of LTE-U and WiFi systems in [56]. According to [53], when the number of SBS users is large, neither QoS of WiFi users nor QoS of LTE-U users can be guaranteed. Therefore, an admission control algorithm needs to used to maximize the number of users served by SBS while guaranteeing the QoS of both LTE-U and WiFi users. The EE issue is also considered for the scenario where licensed channels are shared among SBSs and MBSs. The joint power allocation, licensed and unlicensed spectrum management algorithm in [57] can maximize the system EE. In citeYinaccess, a multi-objective optimization problem is formulated to maximize the EE on both licensed and unlicensed spectra. The above works reveal the relationship between EE on the licensed spectrum and unlicensed spectrum. Compared with the results in [54], it is more complicated and varied in different scenarios due to the frequency reuse on licensed spectrum.

IV. RESOURCE MANAGEMENT IN MULTIPLE SBSS SCENARIO

We have discussed resource management issues for single SBS before. This section focuses on multiple SBSs scenarios where multiple SBSs share unlicensed spectrum, including user association, resource allocation, and spectrum sharing among multiple operators, as summarized in Table 3.

A. USER ASSOCIATION

Compared with the traditional cellular networks that only operate on licensed spectrum, the main challenges of user association in LTE-U systems are two-folds. First, with the integration of licensed and unlicensed spectra in LTE-U SBSs, the user association scenario is more complicated. Second, the QoS of WiFi users should be considered to guarantee harmonious coexistence. These two issues make the algorithms for traditional cellular networks inapplicable for the LTE-U systems.

There are several methods for user association in various LTE-U systems. For the typical user association scenario in [59], each user accesses the licensed channels via orthogonal frequency division multiple access (OFDMA) and aggregates the unlicensed resource via equally sharing the time slots. The proposed user association problem is a mixed-integer non-linear programming (MINLP) and is NP-hard. After appropriate problem transformation and variable relaxation, a centralized upper-bound algorithm has been developed through the sum-of-ratios optimization approach to present a design guideline. Moreover, based on the student project allocation (SPA) approach, a low complexity heuristic algorithm has been obtained for low-latency network design. A joint user association and power allocation problem has been formulated in [60] to maximize the sum rate with consideration of inter-cell interference, where multiple operators and multiple SBSs are considered. A mesh adaptive direct search based heuristic algorithm has been developed to get suboptimal solutions to the formulated problem. QoS-aware user association for LTE-U systems is first investigated in [61]. A joint user association, transmission time period allocation, subcarrier assignment, and power allocation optimization problem is formulated to maximize the number of users served by the LTE-U networks. Four QoS constraints, i.e., throughput and delay guarantee for LTE-U and WiFi users, respectively, are analyzed and considered in the formulated problem. In order to obtain the solutions, the formulated nonlinear and nonconvex problem is decomposed into two subproblems, i.e. the sum-power minimization subproblem and the user association problem. Then, the optimal solutions can be achieved through iteratively solving the two suboptimal solutions until convergence. The LTE-U networks with uplink-downlink decoupling are studied in [62], whereby users can be associated with different SBSs for uplink and downlink transmission. In this scheme, the rate of each SBS depends on both its own choice and the actions of the remaining BSs. The joint user association and resource allocation problem is formulated as a noncooperative game, where the players are SBSs seeking optimal performance and balancing licensed and unlicensed spectra on its own. To solve the problem, an echo state network based machine learning framework has been proposed, which enables each SBS to autonomously learn and schedule its own resources without the coordination among SBSs. Moreover, it has been proved that the proposed framework can converge to a mixed strategy Nash equilibrium, which guarantees fairness among SBSs.

The aforementioned studies on user association mainly focus on the sum rate and are traffic independent. This metric may not reflect a user's QoS with large traffic variation. In [63], the delay optimization of LTE-U systems has been investigated. First, different queueing models are used to distinguish the characteristics of licensed and unlicensed

TABLE 3. Summary of the Literature Focusing on Multiple SBSs Scenario

Theme	Scenario/Characteristic	Design Objective	Reference	Proposed Solution
User association	Considering joint licensed and unlicensed spectrum	Maximizing sum-rate	[59]	Propose an upper-bound algorithm based on sum-of-ratios optimization approach and a heuristic algorithm based on student project allocation approach
	Multiple operators	Maximizing sum-rate	[60]	Propose a joint user association and power allocation algorithm based on a mesh adaptive direct search based heuristic algorithm
	QoS-aware network	Maximizing the number of users served by LTE-U	[61]	Propose a joint user association, time period allocation, subcarrier assignment, and power allocation algorithm
	uplink-downlink decoupling network	Maximizing utility of each user	[62]	Formulate a noncooperative game and propose the optimal solution using echo state network based machine learning framework
Resource allocation	Considering inter-cell interference	Maximizing throughput	[64]	Propose a joint channel assignment and power allocation algorithm based on a delay column generation and a greedy algorithm
	Uplink transmission with backhaul protection	Maximizing system utility	[65]	Propose a joint channel assignment and power allocation algorithm based on Lagrangian relaxation method
	User pairing	Maximizing throughput of LTE and WiFi	[66]	Propose a channel allocation algorithm based on matching theory
	Time variant scheme	Maximizing throughput of LTE-U and WiFi	[67]	Propose a sequential Gale-Shapley algorithm and a random path-to-stability algorithm to manage dynamic channel assignment
		Minimizing power consumption	[68]	Propose a joint unlicensed channel assignment, subcarrier allocation, and power allocation algorithm based on Lyapunov optimization method
	Multiple access	Maximizing system throughput	[69]	Formulate a many-to-many matching game and propose a channel allocation algorithm based on asymmetric student project allocation model
Spectrum sharing among multiple operators	orthogonal access	Optimizing network density	[70]	Develop a theoretical network planning and optimization framework using stochastic geometry
		Maximizing social welfare of each operator	[71]	Formulate a overlapping coalition formation game and propose a distributed alternating direction method with D-ADMM-PVS
		Maximizing network utility	[72]	Propose a bidding fairness access scheme with hybrid HD/FD transmission mode
	Unlicensed spectrum reuse	Maximizing utility for each operator	[73]	Formulate a layered non-cooperative game and propose a zero-determinant power control strategy
			[74]	Formulate a hierarchical game theoretical model and propose a joint power allocation and prices optimization algorithm based on Kalai-Smorodinsky Bargaining Solution
			[75]	Formulate a multi-leader multi-follower Stackelberg game and propose a joint power allocation and prices optimization algorithm for both cooperative and non-cooperative schemes
			[78]	Propose a sharing scheme with dynamic sharing profile and formulate a repeated game to achieve perfect Bayesian equilibrium
			[76]	Propose a joint power and occupancy time allocation algorithm based on Nash bargaining game and Bankruptcy game
		Maximizing QoE of each operator	[77]	Formulate a virtual coalition formation game and propose a joint time sharing and channel assignment algorithm based on cooperative Kalai-Smorodinsky bargaining solution and Q-learning approach
		Maximizing throughput of each operator	[79]	Formulate a noncooperative game and propose a self-organizing channel assignment scheme based on a deep reinforcement learning algorithm with LSTM cells

bands. To minimize the sum of the average packet delay, a joint user association and channel assignment problem is formulated as a bi-convex optimization problem, which can be solved through an iterative algorithm with manageable computational complexity.

B. RESOURCE ALLOCATION

When users are already associated with the local SBS, we can perform channel assignment and power allocation to optimize LTE-U performance. The typical resource allocation scheme in [64] considers the inter-cell interference over licensed and unlicensed spectra among different SBSs. A joint channel assignment and power allocation problem over both licensed and unlicensed bands is formulated to maximize the throughput of the LTE-U network, and is solved via a decomposition method, named as a delay column generation and a greedy algorithm based on Karush-Kuhn-Tucker (KKT) conditions. The work in [65] addresses the similar scenario but with the consideration of backhaul protection.

The matching theory can provide mathematically tractable solutions for combinatorial problems with low computational complexity. It is utilized in [66] to solve the channel assignment problems in multiple SBS scenarios, where virtual unlicensed users are introduced to represent all possible unlicensed users associated with the considered unlicensed channel. The channel assignment problem can be formulated as a matching problem between LTE-U users and virtual users. To find feasible solutions to the given problems, a student project allocation based matching algorithm is developed. Moreover, an inter-channel cooperation subroutine is proposed to deal with the external effect. This work is extended to dynamic resource management in [67]. To tackle resource allocation with time-varying network topology and channel conditions, a sequential Gale-Shapley algorithm is introduced to eliminate the external effect independently in each time scale. However, this algorithm does not consider the relationship between resource allocation for adjacent periods of time. The random path-to-stability algorithm is proposed to address the network dynamics, which makes use of the relations between two-time adjacent matchings. Time variant multi-channel conditions and various network topologies with a random number of WiFi users, are also considered in [68] under a stochastic optimization framework. Here, the optimal unlicensed channel assignment, subcarrier allocation, and power allocation are obtained via the Lyapunov optimization method to minimize system power consumption. Another extended work in [66] considers the scenario where each user can access up to two unlicensed channels and each unlicensed channel can be reused by multiple users [69]. The considered model allows a many-to-many matching game between users and unlicensed channels, which is solved by the proposed asymmetric SPA algorithm.

C. SPECTRUM SHARING AMONG MULTIPLE OPERATORS

The aforementioned studies all focus on resource management for multiple SBSs belonging to the same cellular operator. When there are multiple operators, spectrum sharing among different cellular operators should also be carefully designed, in addition to the coexistence between LTE-U and WiFi. Since the unlicensed spectrum is open to access for different types of RATs, each cellular operator is stimulated to make maximum use of the unlicensed spectrum. This is quite different from licensed spectrum sharing where each operator has exclusive licensed bands. There exist severe inter-operator interference. There are two general approaches to address the issue: the orthogonal access scheme, where each operator selects different unlicensed channels or different time slots to access, and dynamic spectrum sharing, where operators are enabled to reuse some unlicensed channels according to the instantaneous/semi-static traffic load and various channel conditions.

For the orthogonal access scheme, the most straightforward way is to realize time orthogonality, as in [70], where each operator contends for the unlicensed channel through WiFi-like carrier sense multiple access/collision avoidance (CSMA/CA) with different CW sizes and different ED thresholds. This work is extended in [71], with the same CSMA/CA mechanism for time orthogonality, where each operator can negotiate and trade its right to access the unlicensed bands according to the estimated benefit that can be achieved from operating on the unlicensed channel. With this novel design, the operator with insufficient licensed spectrum will be willing to pay more compensation to other operators to trade more transmission opportunities on the unlicensed spectrum, while the operator with enough licensed spectrum resource will have more incentive to sell its rights to other operators. A framework of the overlapping coalition formation game is used to model the negotiation and interaction among multiple operators, where a distributed alternating direction method of multipliers with partial variable splitting (D-ADMM-PVS) is developed to maximize each operator's transferrable utility that represents the benefit of the trade. For the typical unlicensed channel selection scheme for multiple operators in [72], each operator opportunistically bids for the unlicensed channels and starts its transmission if it wins the bidding. With the bidding-based access method, the co-channel interference among multiple operators over unlicensed spectrum can be avoided. Based on this, a bidding based channel selection problem is proposed to maximize the network utility with the consideration of the packet delay constraint and the packet drop rate, where the hybrid FD/ half-duplex (HD) transmission mode is enabled.

There are also several studies on unlicensed spectrum reuse. In [73], a simple spectrum reuse scheme is investigated with single unlicensed channel, where all cellular operators and WiFi APs work simultaneously. By assuming that each operator can only serve one user and each user can only be associated with one operator, a zero-determinant strategy for power control is proposed based on a layered non-cooperative game. This work is extended in [74], where each operator can serve multiple users over multiple unlicensed subbands while each user can be associated with multiple operators simultaneously. Based on this, a joint power allocation and penalty price optimization problem is developed to maximize system utility. A Kalai-Smorodinskt bargaining solution is developed, where multiple operators bargain with each other to obtain fairness. With the same model, a multi-leader multi-follower Stackelberg game is formulated in [75] to further study the interaction between cellular operators and users. As the leaders of the game, operators iteratively update the optimal penalty price based on the predictions of users' behaviour, while the users iteratively update the transmit power based on the penalty price set by operators as the followers of the game. Moreover, two approaches of penalty price setting are proposed for operators, i.e., a non-cooperative approach and a cooperative approach. In the non-cooperative approach, each operator sets its price individually without coordinating with others. In the cooperative approach, all operators set the same price coordinatively. Compared with [75], a more straightforward way to control the impact on WiFi is proposed in [76], where the time-sharing ratio between LTE-U and WiFi systems is considered to realize the time orthogonality. A joint channel

TABLE 4. Summary of the Literature Focusing on LTE-U Related Resource Management Scenarios

Theme	Design Objective	Reference	Proposed Solution
D2D communication	Minimizing interference from D2D users	[83]	Propose a joint mode selection and resource allocation algorithm based on Hungarian algorithm
	Maximizing sum-rate of LTE and D2D-U users	[84]	Propose a joint mode selection, channel assignment, and power allocation algorithm based on particle swarm optimization tools
		[85]	Propose a subchannel allocation algorithm based on many-to-many matching game model
V2X communication	Maximizing sum-rate of V2V users	[90]	Propose a joint power allocation and channel assignment algorithm based on Lagrangian dual method considering latency and reliability requirements
	Maximizing sum-rate of cellular users and V2V users	[91]	Propose a joint spectrum management, power control, and time period allocation strategy based on interior point method and matching algorithm
	Maximizing the number of active V2X users & reducing interference to VANET users	[92]	Propose a joint channel assignment and time period allocation algorithm based on matching theory to realize semi-persistent scheduling for dynamic scenarios
UAV communication	Maximizing capacity & minimizing interference to WiFi	[93]	Propose a RAT selection algorithm and a resource allocation algorithm through a regret based machine learning approach
	Minimizing the number of users that have stable queues	[94]	Propose a joint user association, spectrum management and content caching algorithm based on liquid state machine learning approach

assignment and time sharing allocation problem is formulated to maximize the sum-rate of the LTE-U users while guaranteeing the QoS of the LTE-U and the WiFi users, which is solved with the help of a Nash bargaining game (NBG). The same time orthogonality implementation is utilized in [77], where a typical unlicensed spectrum reuse scheme is proposed. By a virtual coalition formation game, the time sharing ratio is optimized using the cooperative Kalai-Smorodinsky bargaining solution and the channel assignment is solved via a Q-learning approach.

To adapt to dynamic traffic conditions, a spectrum reuse scheme is elucidated in [78], where the spectrum management problem is formulated as a repeated game with private information and communications. Moreover, a dynamic sharing profile is devised in which operators share information about their traffic intensities. With the information in the sharing profile, operators with low traffic load can loan spectrum resources to the operators with high traffic load at any time. A machine learning based optimization method is envisioned as the most promising approach to solve the increasingly sophisticated problems in wireless communications. The work in [79] introduces a long short-term memory (LSTM) cells based deep learning algorithm to develop a proactive spectrum resue scheme. The benefits are two-fold. First, with the LSTM cells, operators have the ability to predict a sequence of interdependent actions over a long-term time horizon, including time-variant channel conditions and network topology. Second, the reinforcement learning based optimization algorithms is more time-efficient to solve the formulated combinatorial problem.

V. LTE-U RELATED RESOURCE MANAGEMENT SCENARIOS

In this section, we will discuss some important resource management issues related to LTE-U systems, including D2D communications, unmanned aerial vehicle (UAV) communications, and vehicle-to-everything (V2X) communications, as summarized in Table 4.

A. D2D COMMUNICATIONS

D2D communications in cellular networks is defined as direct transmission between two uses in proximity without going through the BS. Compared with the conventional cellular communications, D2D communications can achieve proximity gain, hop gain, and reuse gain.

By enabling D2D users to reuse the channels from conventional cellular users, the reuse gain can be achieved. In this case, the mutual co-channel interference between D2D users and cellular users should be carefully coordinated. There are many works on the interference management for D2D communications by channel assignment and power allocation on the licensed spectrum [80], [81]. D2D in unlicensed spectrum (D2D-U), acts as a new paradigm shift for interference management by extending D2D communications to LTE-U networks, as first outlined in [82], to further enhance system throughput. A framework of joint mode selection and resource allocation for D2D-U networks is developed in [83] to minimize the mutual interference from D2D users to cellular and WiFi systems under two different unlicensed channel access schemes, i.e., LBT and CSAT, respectively. It is demonstrated that the introduction of D2D-U can efficiently mitigate the mutual interference caused by D2D users. Moreover, the CSAT channel access scheme always has better performance than the LBT access scheme. This work is extended in [84] to maximize the overall throughput of cellular users and D2D users while considering the QoS of the WiFi users. A joint mode selection, channel assignment, and power allocation method is developed with particle swarm optimization tools. The interference to WiFi networks introduced by LTE-U cellular users and D2D-U users is analyzed in [85], where the subchannel allocation method maximizes the total sum-rate of LTE-U and D2D-U users while limiting the interference to WiFi networks.

B. V2X COMMUNICATIONS

Recently, the concept of V2X communications drew great attention in both industrial and academic fields [86], [87].

It is a promising approach for intelligent transport systems that requires to support a wide variety of safety-critical and traffic-efficient applications. Compared with D2D communications, the design of V2X communications will consider the strict requirements of latency and reliability, as well as mobility [88], [89]. Although dedicated short range communication (DSRC) is already designed for Vehicle Ad-hoc Network (VANET) applications at 5.9 GHz, it has low reliability and spectral efficiency for the contention-based access schemes and short communication range. Therefore, LTE based V2X is studied, which exploits LTE to support V2X communications in licensed spectrum for better performance and wider geographical coverage. Due to spectrum shortage in the licensed spectrum, it is natural to introduce V2X communications to unlicensed spectrum with LTE-U networks. In [90], vehicle-to-vehicle (V2V) communications are allowed to operate on the unlicensed channels via LTE-U SBS. In the developed scheme, the LTE-U SBS divides the V2V users into two parts: those that can utilize the unlicensed bands to serve themselves and those that can only access the licensed bands. A joint power allocation and channel assignment problem is formulated to maximize the performance of V2V users of both parts with consideration for latency and reliability requirements, which can be solved by the Lagrangian dual method with low computational complexity. In [91], vehicular users are classified into two types: safety ones and non-safety ones, according to whether a safety related message is transmitted. On one hand, the safety vehicular users can be only allocated licensed spectrum in order to guarantee reliability. On the other hand, the non-safety vehicular users can access unlicensed channels via two modes: contention period (CP) based WiFi mode, where non-safety services with low priorities contend for unlicensed transmission intervals utilizing CSMA/CA protocol, and contention free period (CFP) based LTE-U mode, where the non-safety services with high priorities can be allocated exclusive resources by LTE-U SBS. Based on this, a resource allocation strategy with low computational complexity is proposed to jointly optimize spectrum management, power control, and CP-CFP time period allocation. The coexistence between unlicensed V2X communications users and VANET users is considered in [92] when both operate on the unlicensed spectrum. A CSAT based spectrum sharing scheme is proposed to reduce the transmission collisions between two RATs, which also considers the dynamic channel conditions by analyzing the velocity of vehicles. Based on this scheme, a joint channel assignment and time period allocation problem is formulated to maximize the number of active V2X users while reducing the interference to VANET users. This problem can be solved by matching theory.

C. UAV COMMUNICATIONS

Due to its unique features of mobility and self-organization, one major application of the aerial wireless communication platforms carried by UAV is to realize the ubiquitous availability of broadband wireless connectivity for public safety scenarios [93]. In this scenario, the most critical bottleneck to support real-time awareness applications is the limited spectrum resource on licensed bands. LTE-U technology is first introduced to the UAV networks in [93], enabling unmanned aerial BSs (UABSs) to utilize the unlicensed spectrum to sustain ubiquitous broadband connectivity during critical emergency situations. By considering a hybrid UABS-WiFi architecture where UABSs and WiFi APs share the unlicensed spectrum via CSAT to serve users, an RAT selection algorithm is proposed between UABSs and WiFi APs with consideration of loads and link qualities. Based on this, a resource allocation problem is formulated as a game, where the goal of each UABS is to maximize their capacity while minimizing interference in WiFi transmission. A regret based machine learning based resource allocation algorithm is proposed to maintain a satisfactory throughput for both UABSs and WiFi APs. In [94], a framework on LTE-U based UAV networks is proposed to further enhance the capacity and coverage of future wireless networks, where users can access both licensed and unlicensed channels. In this scenario, the popular contents are cached at UAVs to reduce the traffic load on the fronthaul links which further improves performance. Users can receive contents from either UAVs directly or via content server-to-UAV-to-user links. A joint user association, spectrum management and content caching problem is formulated for minimizing the number of users that have stable queues. Since each UAV may not know the users content requests, a novel liquid state machine learning approach is proposed to predict the users content request distribution and perform appropriate resource allocation.

VI. FUTURE RESEARCH ISSUES

Even if there have been many research results in the past several years, LTE-U still strives to meet the specific requirements in the ongoing 5 G implementation. In this section, we will provide a brief outlook on resource management of LTE-U in three major 5 G application scenarios, i.e., enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable and low latency communication (URLLC).

A. eMBB

As an evolutionary version of current mobile broadband scenarios, eMBB requires performance improvements and seamless user experience increments for multi-media services. The ultra-dense heterogeneous network, which consists of densely deployed LTE-U SBSs and millimeter-wave (mmWave) APs, has been considered as the emerging cellular network design to address these enhanced requirements. As one important candidate, LTE-U will play an irreplaceable role. However, there are many challenges on LTE-U in the ultra-dense heterogeneous network. In the following, we will discuss the research problems related to LTE-U designed for eMBB from the perspective of an ultra-dense heterogeneous network.

1) NETWORK ARCHITECTURE DESIGN

Due to the densification of LTE-U SBSs and mmWave APs, the architecture of the ultra-dense heterogeneous network should be carefully designed. Driven by reducing the computational complexity of user scheduling and resource management, a layered architecture is predicted for 5 G in the future. By analogy to existing studies focusing on ultra-dense mmWave networks, such as [95], it is intuitive to design a basic two-tier hierarchical architecture where the top tier consists of LTE-U SBSs focusing on network control, information measurement, and control signaling transmission, while the second tier consists of mmWave APs focusing on data transmission. However, it also brings difficulties in its adoption to various environments with different traffic load intensities and distributions. For example, in the scenario of high traffic load and densely deployed LTE-U SBSs and mmWave APs, more tiers need to be involved to reduce the computational complexity. On the other hand, in a scenario with few users and low density of LTE-U SBSs and mmWave APs, the architecture should be simplified to reduce the communication cost between different tiers.

2) DENSITY PLANNING

A heterogeneous network consists of different types of cells and APs operating on different frequency bands and providing different levels of data traffic for various applications. How to efficiently plan the density, i.e., the number of different types of cells and APs, is the pivotal challenge for the heterogeneous network design. Generally, density planning highly depends on the data requirement of users, which is dynamic and needs prediction. Two key factors should be addressed for the LTE-U SBSs, i.e., the sophisticated co-channel interference over licensed and unlicensed spectrum among LTE-U SBSs, and the increasing collision probability in WiFi systems caused by the transmissions of LTE-U. These impacts may be captured by stochastic geometry tools.

3) USER ASSOCIATION

The user association of the ultra-dense heterogeneous networks consisting of LTE-U SBSs and mmWave APs is still an open issue. Several key challenges should be addressed. The first one is the coordination of RAT selection. As stated in [46], users with different data traffic requirements prefer to be associated with different types of cells and APs. When LTE-U SBSs/mmWave APs are not enough, there must be users who cannot access to their first choice. Therefore, the efficient coordination algorithms for RAT selection should be investigated in the future. The second one is multi-connectivity, which enables users to access multiple cells or APs. Generally, there are two type of users who are appropriate for implementing the multi-connectivity. One is the users that need to access multiple mmWave APs to achieve ultra-high data rates while the other one is the users that have to access multiple LTE-U SBSs due to the lack of mmWave APs and its high traffic load requirements. The multi-connectivity design makes current studies not readily applicable. One feasible solution is to treat the user association problems as many-to-many matching games. Moreover, the machine learning tools have great potential to solve this type of problem, such as the multi-label classification algorithms.

4) RESOURCE ALLOCATION

Several key challenges should be addressed for the resource management of ultra-dense heterogeneous networks. First, most existing works have investigated efficient resource allocation algorithms when complete CSI is available. However, the overhead to obtain accurate CSI is always high. It is even worse when considering dense implementation over licensed, unlicensed and mmWave frequency bands. Appropriate probabilistic resource allocation with partial CSI information or even only distance information should be investigated in the future. Second, different from the traditional LTE systems, future 5 G has distinct performance indicators that impact quality-of-experience (QoE) of users, such as cost and reliability. However, most existing works only focus on relevant indicators related to data rate, such as spectrum efficiency, system throughput, and utility function based on data rate. To give a comprehensive prospective of the heterogeneous systems, these significant performance indicators should be also involved in resource allocation framework. Specifically, there exists an intrinsic tradeoff among the data rate, cost, and reliability. For instance, lower cost always leads to more unlicensed spectrum resources while the data rate and reliability will be degraded since the unlicensed spectrum is always less reliable than licensed spectrum. Maximizing the global QoE considering these performance indicators to achieve an excellent balance is an important research topic.

B. mMTC

In mMTC, fully automatic, relative low volume, and non-delay sensitive data transmission would happen in a huge number of intelligent sensors with low device cost. There are two potential benefits of introducing LTE-U to mMTC. First, mMTC may occur in remote areas without LTE network coverage, such as a refinery or a basement. To enable the transmission in these very confined and coverage-limited locations, MulteFire can be introduced to support mMTC, which operates the LTE-based technology solely on unlicensed spectrum and can be configured by users themselves. Second, one design principle of mMTC is to guarantee the performance of traditional human-type communications. Therefore, LTE-U can be utilized to release the severe co-channel interference on licensed spectrum between mMTC and traditional communications. Despite these potential benefits, several obstacles are still challenging, including access management and large-scale resource management.

1) ACCESS MANAGEMENT

Due to the simultaneous access of massive MTC equipment, it is appropriate to enable nonorthogonal multiple access

(NOMA) for mMTC, which utilizes power-domain user multiplexing by configuring more power to weak users with low channel gain and less power to strong users with high channel gain [96], [97]. However, transmission power over unlicensed spectrum is limited due to the requirements of ETSI. The limitation of transmission power may affect the performance of unlicensed NOMA, even cause the failure of the successive interference cancellation procedure during decoding. Therefore, the appropriate design of unlicensed NOMA, especially the power control, should be addressed for access management of mMTC.

2) LARGE-SCALE RESOURCE MANAGEMENT

The management of wireless connectivity to massive MTC equipment leads to large-scale resource optimization problems. To reduce signaling overhead and computational complexity, it is appropriate to design game theoretical based algorithms, which have been widely investigated to solve resource management problems. Generally, game theory can be utilized to treat the scenario with any number of users. However, the tremendous number of MTC terminals will make the computational complexity of the current game theory algorithms rise dramatically, especially with the consideration of both licensed and unlicensed spectrum. Novel game theory tools are required for mMTC. One feasible solution is the mean-field game, where the interaction among numerous MTC equipments can be formulated as mean field interference following the global response of all elements within the network [98]. Another potential approach is the non-atomic game, where the impact of any single MTC equipment on the performance of other MTC equipment is negligible [99]. Moreover, random matrix theory can be applied to single out the main parameters of interest that determine performance [100].

3) ENERGY HARVESTING

To enable MTC devices to maintain long-time connectivity without recharging, energy harvesting technique has been introduced to mMTC [101]. Offloading energy harvesting of mMTC to unlicensed spectrum has a great possibility to achieve good performance since the licensed spectrum is always overloading. The study in [102] investigates a basic scenario where devices receive energy over unlicensed spectrum and transmit data over licensed spectrum. However, a much better performance is predicted when licensed and unlicensed spectra are both enabled to transmit data and receive data, something that needs efficient algorithms to jointly consider licensed and unlicensed resource management.

C. URLLC

The applications of URLLC have stringent requirements on delay and reliability. To improve robustness as well as reduce latency, it is natural to introduce LTE-U to URLLC as a supplement of communications on licensed spectrum. Several challenges of LTE-U in URLLC have been stated in the aforementioned paragraph, such as QoE-based resource management in eMBB, and unlicensed NOMA in mMTC. Cooperative relaying has been considered as an efficient strategy to enhance transmission reliability and achieve low latency. Introducing relay enabled LTE-U to URLLC has a great opportunity to obtain better performance. However, the relaying in LTE-U is still an open issue. Several fundamental configurations need to be designed carefully. The first one is the choice between the amplify-and-forward relays and decode-and-forward relays. The second one is the choice between half-duplex relays and full-duplex relays. The third one is the design of the backhual links of relay communications, licensed bands and unlicensed bands namely, which one is better? Because of the different transmission characteristics of LTE-U and different models of URLLC, the results of these problems may be different from that of traditional licensed communications. Besides these issues, power allocation under the limits of unlicensed transmission is also a challenging problem.

VII. CONCLUSION

LTE-U is an innovative technology that enables the 3GPP LTE systems to work on the unlicensed 5 GHz spectrum. In this article, we provide a comprehensive survey for resource management in LTE-U systems. Several major topics are studied. The first is related to the single SBS scenario, focusing on RAT selection, traffic offloading, and resource allocation. The second topic is related to the multiple SBS scenario, where the issues of user association, resource allocation, and spectrum sharing are discussed. Besides, we also discuss LTE-U related techniques, including D2D communications, V2X communications, and UAV communications. The paper ends with a discussion of open research directions. Our comprehensive survey on resource management in LTE-U in this article will hopefully provide valuable references and guidelines for further in-depth research in this area.

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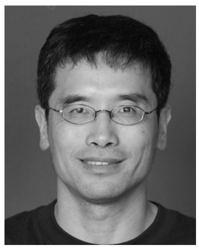
RUI LIU received the B.S.E. degree from Zhejiang University, Hangzhou, China, in 2016, where he is currently working towards the Ph.D degree with the College of Information Science and Electronic Engineering. Since December 2018, he has been working as a Visiting Student with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA. His general research interests include LTE in unlicensed spectrum, millimeter-wave (mmWave) communications, and machine learning for wireless networks.

QIMEI CHEN (Member, IEEE) received the Ph.D. degree in communication engineering from Zhejiang University, Hangzhou, China, in 2017. From 2015 to 2016, she was a Visiting Research Scholar with the School of Electrical and Computer Engineering, University of California, Davis, CA, USA. She is currently an Associate Researcher with the School of Electronic Information, Wuhan University, Wuhan, China. She received the Excellence Award of Excellent Ph.D. Thesis of China Electronics Society in 2017, Chu Kochen Scholarship at Zhejiang University in 2016, and the Ph.D. Researcher National Scholarship in 2015. Her general research interests include 5G communications, WLAN, and energy-efficient communication techniques in next-generation wireless communication systems.

GUANDING YU (Senior Member, IEEE) received the B.E. and Ph.D. degrees in communication engineering from Zhejiang University, Hangzhou, China, in 2001 and 2006, respectively. He joined Zhejiang University in 2006, and is currently a Full Professor with the College of Information and Electronic Engineering. From 2013 to 2015, he was also a Visiting Professor with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA. His research interests include 5G communications and networks, mobile edge computing, and machine learning for wireless networks.

Dr. Yu has served as a Guest Editor of IEEE Communications Magazine Special Issue on Full-Duplex Communications, an Editor of IEEE Journal on Selected Areas in Communications Series on Green Communications and Networking, and a lead Guest Editor of IEEE Wireless Communications Magazine Special Issue on LTE in Unlicensed Spectrum, and an Editor of IEEE Access. He is now serving as an Editor of IEEE Transactions on Green Communications and Networking and an Editor of IEEE Wireless Communications Letters. He received the 2016 IEEE ComSoc Asia-Pacific Outstanding Young Researcher Award. He regularly sits on the Technical Program Committee boards of prominent IEEE conferences such as ICC, GLOBECOM, and VTC. He also serves as a Symposium Co-Chair for IEEE Globecom 2019 and a Track Chair for IEEE VTC 2019'Fall.

GEOFFREY YE LI (Fellow, IEEE) is a Professor at the Georgia Institute of Technology, Atlanta, GA, USA. Before moving to Georgia Tech, he was with AT&T Labs - Research at Red Bank, NJ, USA, as a Senior and then a Principal Technical Staff Member from 1996 to 2000, and a Postdoctoral Research Associate with the University of Maryland at College Park, MD, USA, from 1994 to 1996. His general research interests include statistical signal processing and machine learning for wireless communications. In these areas, he has published more than 500 journal and conference papers in addition to over 40 granted patents. His publications have been cited more than 37 000 times and he has been recognized as the Worlds Most Influential Scientific Mind, also known as a highly-cited researcher, by Thomson Reuters almost every year. He was awarded as IEEE Fellow for his contributions to signal processing for wireless communications in 2005. He won several prestigious awards from IEEE Signal Processing Society (Donald G. Fink Overview Paper Award in 2017), IEEE Vehicular Technology Society (James Evans Avant Garde Award in 2013 and Jack Neubauer Memorial Award in 2014), and IEEE Communications Sociaty (Stephen O. Rice Prize Paper Award in 2013, Award for Advances in Communication in 2017, and Edwin Howard Armstrong Achievement Award in 2019). He also received 2015 Distinguished Faculty Achievement Award from the School of Electrical and Computer Engineering, Georgia Tech. He has been involved in editorial activities for over 20 technical journals for the IEEE, including founding Editor-in-Chief of IEEE 5 G Tech Focus. He has organized and chaired various international conferences, including the Technical Program Vice-Chair of IEEE ICC03, the Technical Program Co-Chair of IEEE SPAWC11, the General Chair of IEEE GlobalSIP14, the Technical Program Co-Chair of IEEE VTC16 (Spring), and the General Co-Chair of IEEE VTC19 (Fall).



ZHI DING (Fellow, IEEE) received the Ph.D. degree in electrical engineering from Cornell University, Ithaca, NY, USA, in 1990. From 1990 to 2000, he was a Faculty Member of Auburn University and later University of Iowa. He has held visiting positions in Australian National University, Hong Kong University of Science and Technology, NASA Lewis Research Center and USAF Wright Laboratory. He has active collaboration with researchers from Australia, Canada, China, Finland, Hong Kong, Japan, Korea, Singapore, and Taiwan. He is a Professor of electrical and computer engineering, University of California, Davis.

Dr. Ding is serving on technical programs of several workshops and conferences. He was an Associate Editor for IEEE Transactions on Signal Processing from 1994–1997, 2001–2004, and an Associate Editor of IEEE Signal Processing Letters 2002–2005. He was a member of technical committee on Statistical Signal and Array Processing and member of technical committee on Signal Processing for Communications (1994–2003). He was the General Chair of the 2016 IEEE International Conference on Acoustics, Speech, and Signal Processing and the Technical Program Chair of the 2006 IEEE Globecom. He was also an IEEE Distinguished Lecturer (Circuits and Systems Society, 2004–2006, Communications Society, 2008–2009). He served as IEEE Transactions on Wireless Communications Steering Committee Member (2007–2009) and its Chair (2009-2010). He is a coauthor of the text: *Modern Digital and Analog Communication Systems*, 5th edition, Oxford University Press, 2019.