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Proportional Fairness-Based Resource Allocation for LTE-U Coexisting With Wi-Fi

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ABSTRACT To further boost the performance of LTE to meet the ever-increasing mobile traffic demand in a cost-effective way, applying LTE in unlicensed spectrum, known as LTE-U technology, is considered as a promising complementary solution for achieving the ultra-capacity foreseen in 5G and beyond. In the unlicensed spectrum, LTE-U will share the channel with other unlicensed networks, e.g., Wi-Fi. However, the centralized control architecture of LTE networks is inherently different from the distributed channel access of Wi-Fi network, which poses great challenges to achieve fair coexistence of the two networks. To this end, in this paper, we propose a cross-layer proportional fairness (PF)-based framework to jointly optimize the protocol parameters of the medium access control layer and physical layer of an LTE-U network. Specifically, to achieve throughput-oriented PF between the two heterogeneous networks, the cross-layer optimization framework can be decoupled into a device number weighted time occupation ratio-oriented PF optimization problem and a channel-power allocation-based instantaneous transmission rate-oriented PF optimization problem. Given that LTE-U base stations adopt a listen-before-talk-based channel access scheme, the interactions between the LTE-U and the Wi-Fi networks are modeled by two interactive Markov chains. The effectiveness and the superior performance of the proposed cross-layer PF-based optimization framework are demonstrated and verified by simulations.

INDEX TERMS LTE-U, Wi-Fi, proportional fairness, MAC modeling, cross-layer design.

I. INTRODUCTION

According to a recent release of Cisco's Global mobile data traffic forecast update [1], there will be 11.5 billion mobile-connected devices by 2019, exceeding the world's projected population at that time (7.6 billion). With such phenomenal proliferation of smart devices and applications, the soaring mobile data growth poses a significant challenge to wireless operators for the evolution of the existing wireless network architecture. Different emerging technologies have been developed for long-term evolution (LTE) and LTE-Advanced networks to provide a diversity of multimedia applications with sufficient network capacity and quality of service (QoS) guarantee, such as non-orthogonal multiple access, massive multi-input multi-output, small cell, and context awareness [2]–[5]. However, the limited spectrum resource is the fundamental bottleneck for capacity improvement.

To cope with such challenges, applying LTE in unlicensed spectrum, known as LTE-U, is considered as a promising complementary solution by providing flexible and maximal spectrum usage to support the ultra-capacity foreseen by 5G and beyond. Due to the centralized channel-aware scheduling, LTE-U is expected to extend the advantages of LTE/LTE-A to unlicensed spectrum via offering consumers more robust broadband experience with better coverage and higher transmission rates. In 2014, the LTE-U Forum was formed by Verizon in cooperation with Alcatel-Lucent, Ericsson, Qualcomm Technologies, Inc., a subsidiary of

Qualcomm Incorporated, and Samsung to generate the technical specifications for LTE-U. In June 2014, a workshop was hold by 3GPP to define the future technical scope of LTE-U project, which is considered as "fruitful contribution to the start of work in the project". In the recent published technical report for 3GPP Release 13, some standards have been specified for LTE-U in terms of the frame structure and listen-before-talk (LBT) procedure in licensed-assisted access LTE (LAA-LTE) downlink transmission [6].

However, the rapid evolution of LTE-U standardization raises significant concerns, especially in the Wi-Fi industry, about whether LTE-U will harmoniously coexist and fairly share the unlicensed spectrum with the IEEE 802.11 users. Due to the dissimilar access mechanisms of LTE and other legacy technologies in unlicensed bands, such as Wi-Fi, applying the LTE technology directly in the unlicensed spectrum may lead to severe starvation of the incumbent contention-based networks operating in the same unlicensed bands. Some simulation results have revealed that the simultaneous operation of LTE and Wi-Fi in the same spectrum bands will fiercely degrade the performance of Wi-Fi networks [7]. Therefore, it is critical to design LTE-U channel access mechanism and/or its radio resource allocation methods to guarantee harmonious coexistence, providing both LTE-U and Wi-Fi fair opportunities to access the unlicensed bands.

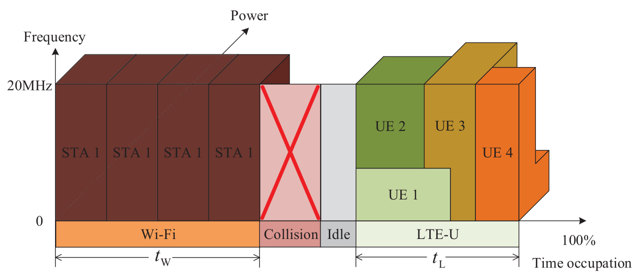

FIGURE 1. Resource architecture in a 20MHz channel of the unlicensed band: time, frequency, power.

In this paper, we consider an LTE-U network with LTE-U base station (BS) and LTE-U user equipments (UEs) coexisting with Wi-Fi networks and propose a general resource allocation framework in the unlicensed band to achieve the harmonious sharing among all the LTE-U UEs and Wi-Fi stations (STAs). As shown in Fig. 1, on the one hand, in the time domain we should allocate the two networks with appropriate proportion of the channel occupation; on the other hand, in the LTE-U internal network, the time-frequency allocation and power allocation among the associated UEs should be scheduled to improve the network capacity and ensure the overall fairness requirement. Because in the unlicensed band the LTE-U network and Wi-Fi network make up a distributed system, LTE-U's centrally determining the time occupation ratio of the two networks is not allowed. A more feasible way is to change the parameters of its channel access (e.g., the frequency of channel access attempts, the occupation time of one successful access) to adjust the time occupation ratio of the two networks, which is also challenging for implementation due to the complicated interaction of the two networks. Meanwhile, the time-frequency allocation and power allocation in the LTE-U network are closely related to the results of time occupation ratio and have significant effect on the fairness of the allocation.

In the following, we propose a cross-layer proportional fairness (PF)-based framework to jointly optimize the protocol parameters of the medium access control (MAC) layer and the physical layer of an LTE-U network. The main contributions of this paper are threefold.

- Based on a utility-optimization-based architecture, we propose a generic cross-layer framework for the LTE-U downlink resource allocation to achieve PF among all the devices in both LTE-U and Wi-Fi networks. By exploiting the coupling relationship between the MAC layer and the physical layer and the interaction between LTE-U BS and Wi-Fi STAs, we show that the proposed optimization framework can be decoupled to two independent suboptimization problems, solved in the MAC and physical layers, respectively.
- To verify the effectiveness of the proposed general intersystem optimization framework, we further propose an LBT-based channel access scheme for the LTE-U network, where the LTE-U BS can adapt the access frequency and the occupation time by adjusting the contention window of its LBT-based sensing. Under this mechanism, we also develop two interactive Markov models to theoretically analyze the network performance of LTE-U and Wi-Fi, which can be integrated into the aforesaid optimization framework to provide the two networks' channel occupation time ratio.
- Simulations are performed to validate the correctness of our analytical model for the coexisting networks and the effectiveness of the proposed PF-based resource allocation framework. Furthermore, we show that by applying our proposed resource allocation method, the LTE-U network can behave as a good neighbour of a Wi-Fi network.

The rest of the paper is organized as follows. In Section II, we review the previous work about how to facilitate the coexistence of the LTE-U network and the Wi-Fi network. In Section III, we introduce the generic analytical framework of PF-based resource allocation. In Section IV, we propose an LBT-based channel sharing mechanism for LTE-U network and present the theoretical modeling of the proposed coexistence mechanism. Simulation results are given in Section V, followed by the conclusions and the discussions on the future work in Section VI.

II. RELATED WORK

In recent years, there are many works studying how to guarantee the fair coexistence between LTE-U networks and Wi-Fi networks. In [8], Fuad M. Abinader et al. discussed some possible coexistence mechanisms which could be applied in future LTE-U network: flexible spectrum access, channel selection, blank subframes, and transmit power control. Accordingly, an almost blank subframe (ABS)-based network architecture was proposed in [9] for the coexistence of Wi-Fi and heterogeneous small cellular networks, where the mitigation of the co-channel interference from small cells to Wi-Fi networks was also taken into consideration. In [10], under a carrier sense adaptive transmission (CSAT) gating cycle mechanism for LTE-U transmission, an unlicensed spectrum inter-cell interference coordination mechanism was proposed to significantly promote the LTE-U network's performance for multi-operator LTE-U co-channel coexistence.

However, neither the ABS or the CSAT obeys the LBT requirements which are mandated for unlicensed spectrum access in many countries [11], [12]. The ABSs are LTE subframes with degraded transmission power originally intended for interference coordination and when they are applied in the coexistence with Wi-Fi networks in unlicensed band, they can reduce the interference to Wi-Fi networks. The CSAT allows the LTE-U network to share the unlicensed band with Wi-Fi networks via time division multiplexing. Even considering fairly sharing with Wi-Fi networks, such proprietary access mechanisms may result in a high probability that the selfish off/on switch of LTE-U will imprudently interrupt the ongoing transmission of a Wi-Fi STA. As such, in this work, we introduce an LBT-based coexistence mechanism to protect Wi-Fi transmissions.

In [13], a resource allocation scheme was proposed to balance the traffic over licensed band and unlicensed band while the throughput of Wi-Fi network is maintained via a utility-based optimization framework. In [14], a novel proportional fair allocation scheme was proposed to ensure fair coexistence between LTE-U and Wi-Fi networks. However, in [13] and [14], only one UE is considered in the LTE-U network while resource allocation for a multiple-UE scenario requires considerable efforts to achieve the harmonious coexistence among all the devices of interest which is the main objective of this work. In [15], a hybrid method combining traffic offloading and resource sharing methods was proposed to deliver cellular data traffic over unlicensed bands. However, when adopting the resource sharing method, the occupation of LTE-U network will change the behavior of Wi-Fi network, which had not been considered. In this work, the interaction of the LBT-based LTE-U network and the contention based Wi-Fi network are considered in the coexistence scenario, which results in a more precise model.

III. ANALYTICAL FRAMEWORK OF PF-BASED RESOURCE ALLOCATION

We consider the deployment scenario as shown in Fig. 2, where K_{W} Wi-Fi STAs, an LBT-enabled LTE-U BS, and its K_{L} associated LTE-U UEs operate in a channel of the 5GHz unlicensed band. In the LTE-U network, the channel with bandwidth B is further divided into N subcarriers to support the orthogonal frequency-division multiplexing access (OFDMA)-based downlink transmissions. All Wi-Fi STAs' access and transmission comply with the IEEE 802.11 protocol and the LTE-U UEs' transmission is scheduled by the LBT-based LTE-U BS. All the Wi-Fi STAs, LTE-U BS, and LTE-U UEs are assumed to have full-buffer traffic and are fully connected, i.e., there is no hidden terminal problem.

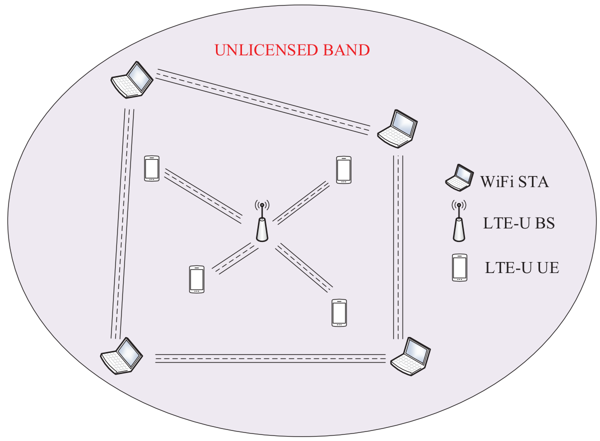

FIGURE 2. Deployment scenario.

Due to the interaction between the Wi-Fi and LTE-U networks, the channel occupation pattern of Wi-Fi STAs with CSMA/CA will vary. To facilitate the mathematical representation, the contention-based interaction result between Wi-Fi and LTE-U networks is abstracted as the ratio of channel occupation time of the Wi-Fi network denoted as t_{W} and that of the LTE-U network t_{L} (see Fig. 1). It should be noted that both t_{W} and t_{L} are only referred to as the time of successful transmissions, that is, the collision and waiting time is not included.

Aiming at formulating the PF-based resource allocation as a general framework for any potential coexistence mechanism, we introduce a MAC-dependent set $\mathcal{A}$ to represent the feasible region consisting of all possible combinations of $(t_{\mathrm{W}}, t_{\mathrm{L}})$. Obviously, $\mathcal{A}$ is a subset of $[0, 1]^2$ and when all the devices are fully-connected, we have $t_{\mathrm{W}} + t_{\mathrm{L}} < 1$. The average throughput of Wi-Fi STAs and LTE-U UEs depends on not only the adopted modulation and coding scheme but also the transmission time ratio. In the Wi-Fi network, at any instant only one Wi-Fi STA is transmitting over the whole spectrum band except a collision happens. Because all STAs have the same contention configuration, each STA will have equal time occupation on average, i.e., $t_{\mathrm{W}}/K_{\mathrm{W}}$. So the average throughput of each Wi-Fi STA j can be denoted as $S_j^{\mathrm{W}} = \frac{t_{\mathrm{W}}}{K_{\mathrm{W}}} R_j^{\mathrm{W}}$, where R_j^{W} is the instantaneous transmission rate according to the signal-to-interference-plus-noise ratio (SINR) and the PHY specifications of the IEEE 802.11 protocol. On the contrary, downlink transmission in an LTE-U cell is based on OFDMA, which enables a BS to transmit to multiple UEs simultaneously. Because the specific modulation and coding scheme that will be applied in the future LTE-U network has not been determined, we denote the achievable transmission efficiency of user k on subcarrier n as

$$c_{k,n}=\log_2\left(1+\frac{\beta p_n|h_{k,n}|^2}{N_0B/N}\right) \tag{1}$$

where p_n is power allocated to subcarrier n, $h_{k,n}$ is the channel gain of LTE-U UE k on subcarrier n, and N_0 is the noise spectral density. Besides, β is a constant specified in [16] related to a targeted bit-error rate (BER) by

$$\beta=1.5/(\text{-}\ln(5\text{BER})). \tag{2}$$

Therefore, the instantaneous throughput of user k can be denoted as

$$R_k^{\mathrm{L}}=\frac{B}{N}\sum_{n=1}^{N}x_{k,n}c_{k,n}. \tag{3}$$

Here, $x_{k,n}$ is the subcarrier allocation result, where $x_{k,n}=1$ means that subcarrier n is allocated to UE k and $x_{k,n}=0$ means the opposite case; so the throughput of the LTE-U UE k given a fixed channel gain is denoted as

$$S_k^{\mathrm{L}}=t_{\mathrm{L}}R_k^{\mathrm{L}}. \tag{4}$$

To achieve the harmonious coexistence in unlicensed spectrum, the LTE-U should take considerable care to protect the performance of incumbent Wi-Fi networks. Taking both efficiency and fairness in the heterogeneous network into account [17], the utility of any device in the unlicensed band is defined as the logarithm function about its throughput in (5) to achieve a proportional fairness-based resource allocation

$$U(S)=\log(S). \tag{5}$$

Therefore, an optimization framework is formulated in (6) to maximize all the devices' throughput-dependent utility by determining the time sharing $(t_{\mathrm{L}},t_{\mathrm{W}})$ between the LTE-U and Wi-Fi networks and the subcarrier-power allocation $(x_{k,n},p_n)$ for the N subcarriers among the K_{L} UEs in the LTE-U network as follows:

$$\text{OP1:}\begin{cases}\max\limits_{t_{\mathrm{W}},t_{\mathrm{L}},x_{k,n},p_n} F(t_{\mathrm{W}},t_{\mathrm{L}},x_{k,n},p_n)\\ \quad=\mathbb{E}\left(\alpha\sum_{k=1}^{K_{\mathrm{L}}}\log\left(S_k^{\mathrm{L}}\right)+(1-\alpha)\sum_{j=1}^{K_{\mathrm{W}}}\log\left(S_j^{\mathrm{W}}\right)\right) & \text{(6a)}\\ \text{s.t. C1: } x_{k,n}\in\{0,1\},\quad\forall k,\ \forall n & \text{(6b)}\\ \quad\text{C2: } \sum_{k=1}^{K_{\mathrm{L}}}x_{k,n}\le 1,\quad\forall n & \text{(6c)}\\ \quad\text{C3: } \sum_{n=1}^{N}\sum_{k=1}^{K_{\mathrm{L}}}x_{k,n}p_n\le P_{\mathrm{total}} & \text{(6d)}\\ \quad\text{C4: } p_n\ge 0,\quad\forall n & \text{(6e)}\\ \quad\text{C5: } (t_{\mathrm{L}},t_{\mathrm{W}})\in\mathcal{A} & \text{(6f)}\end{cases}$$

where $\mathbb{E}(\cdot)$ denotes expectation and depends on the stochastic channel gain, channel's availability, and also the resource allocation scheme. α is a weighting factor which can be finely tuned to satisfy a required resource sharing result. Normally, if LTE-U UEs and Wi-Fi STAs are considered with equal importance, α can be simply set as 0.5. However, some IEEE 802.11 organizations maintain that the appearance of LTE-U will degrade the performance of Wi-Fi STAs seriously, therefore, its value may be less than 0.5, which means that the Wi-Fi network is paid more attention to. In this work, we aim at proposing a general framework to address the coexistence issue and the setting of α's value can be decided by future standards or regulations. Constraint C1 and C2 require that each subcarrier can only be allocated to only one user, C3 and C4 describe the overall power constraint with P_{total} denoting the LTE-U BS's maximum transmission power allowed, and C5 gives the coupling relationship between the two networks' occupation time.

The coupling interaction between different layers and networks make the optimization framework difficult to be solved directly. Fortunately, via some mathematical derivations, we can decouple OP1 into two subproblems according to (7), as shown at the bottom of this page,

$$\begin{aligned}F(t_{\mathrm{L}},t_{\mathrm{W}},x_{k,n},p_n)&=\mathbb{E}\left(\alpha\sum_{k=1}^{K_{\mathrm{L}}}\log(t_{\mathrm{L}}R_k^{\mathrm{L}})+(1-\alpha)\sum_{j=1}^{K_{\mathrm{W}}}\log(\frac{t_{\mathrm{W}}}{K_{\mathrm{W}}}R_j^{\mathrm{W}})\right)\\&=\alpha\mathbb{E}\left(K_{\mathrm{L}}\log(t_{\mathrm{L}})+\sum_{k=1}^{K_{\mathrm{L}}}\log(R_k^{\mathrm{L}})\right)+(1-\alpha)\mathbb{E}\left(K_{\mathrm{W}}\log(t_{\mathrm{W}})+\sum_{j=1}^{K_{\mathrm{W}}}\log(R_j^{\mathrm{W}})-K_{\mathrm{W}}\log(K_{\mathrm{W}})\right)\\&=\underbrace{\alpha K_{\mathrm{L}}\log(t_{\mathrm{L}})+(1-\alpha)K_{\mathrm{W}}\log(t_{\mathrm{W}})}_{F_1}+\underbrace{\alpha\mathbb{E}\left(\sum_{k=1}^{K_{\mathrm{L}}}\log(R_k^{\mathrm{L}})\right)}_{F_2}+\underbrace{(1-\alpha)\mathbb{E}\left(\sum_{j=1}^{K_{\mathrm{W}}}\log(R_j^{\mathrm{W}})-K_{\mathrm{W}}\log(K_{\mathrm{W}})\right)}_{\text{Constant } C}\\&=F_1(t_{\mathrm{L}},t_{\mathrm{W}})+F_2(c_{k,n},p_n)+C\end{aligned} \tag{7}$$

where

$$F_1(t_\mathrm{L}, t_\mathrm{W}) = \alpha K_\mathrm{L}\log(t_\mathrm{L}) + (1-\alpha)K_\mathrm{W}\log(t_\mathrm{W}) \tag{8}$$

$$F_2(c_{k,n}, p_n) = \alpha\mathbb{E}\left(\sum_{k=1}^{K_\mathrm{L}}\log(R_k^\mathrm{L})\right) \tag{9}$$

$$C = (1-\alpha)\mathbb{E}\left(\sum_{j=1}^{K_\mathrm{W}}\log(R_j^\mathrm{W}) - K_\mathrm{W}\log(K_\mathrm{W})\right). \tag{10}$$

Because C in (7) is a constant depending only on the basic configuration of the Wi-Fi network, the original optimization problem can be further divided into an occupation time ratio-related problem and an LTE-U internal PF-based resource allocation problem. That is, in the MAC layer, the occupation time ratio of LTE-U network and that of Wi-Fi network should be allocated by maximizing F_1. On the other hand, in the physical layer, we should maximize F_2, which always maximizes the sum of the instantaneous-throughput-related utility in all scenarios with different channel qualities. Therefore, we can decouple OP1 into the following sub-optimization problems and obtain the proportional fairness's necessary and sufficient conditions.

1) In terms of the time occupation ratio, the device number dependent utility function related to the time occupation ratio should be maximized:

$$\text{OP2:} \begin{cases} \max\limits_{t_\mathrm{L}, t_\mathrm{W}} \ \alpha K_\mathrm{L}\log(t_\mathrm{L}) + (1-\alpha)K_\mathrm{W}\log(t_\mathrm{W}) \\ \text{s.t. C5: } (t_\mathrm{L}, t_\mathrm{W}) \in \mathcal{A}. \end{cases} \tag{11}$$

2) When the channel is occupied by the LTE-U, the subcarrier assignment and the power allocation should be scheduled to achieve proportional fairness among only LTE-U UEs:

$$\text{OP3:} \begin{cases} \max\limits_{x_{k,n}, p_n} \sum_{k=1}^{K_\mathrm{L}} \log(R_k^\mathrm{L}) & \text{(12a)} \\ \text{s.t. C1: } x_{k,n} \in \{0,1\}, \quad \forall k, \ \forall n & \text{(12b)} \\ \quad \text{C2: } \sum_{k=1}^{K_\mathrm{L}} x_{k,n} \le 1, \quad \forall n & \text{(12c)} \\ \quad \text{C3: } \sum_{n=1}^{N}\sum_{k=1}^{K_\mathrm{L}} x_{k,n}p_n \le P_\mathrm{total} & \text{(12d)} \\ \quad \text{C4: } p_n \ge 0, \quad \forall n. & \text{(12e)} \end{cases}$$

The solution to OP2 is based on the knowledge of the feasible region of $(t_\mathrm{L}, t_\mathrm{W})$, i.e., $\mathcal{A}$, which depends on the MAC protocol adopted in LTE-U networks. By considering an LBT-based channel sharing scheme for LTE-U network, we will discuss the solution to OP2 in further details in Section IV.

In OP3, it is a utility-based resource allocation problem in OFDMA-based wireless broadband networks. Note that the utility function is nonlinear and to solve $x_{k,n}$ has an integer constraint, making the problem challenging to solve. In [18], an algorithm combining dynamic subcarrier assignment and adaptive power allocation is proposed to solve it via an iterative method. The basic idea of the solution can be divided into two parts:

Algorithm 1 Joint Subcarrier Assignment and Power Allocation

Initialize: Subcarriers are randomly assigned to LTE-U UEs and each subcarrier is allocated with equal power; $i = 0$, $\gamma_k^i = 0$, $\forall k$;

Iteration until $\sum_{k=1}^{K_\mathrm{L}} U'\left(R_k^\mathrm{L}\right)\left|R_k^\mathrm{L} - R_k'^\mathrm{L}\right| < \varepsilon$

(1) Get the new subcarrier assignment using
$m(n) = \arg\max\limits_k\{\gamma_k^i c_{k,n}\}$, $x_{m(n),n} = 1, \forall n$;

(2) Get the new power allocation scheme
$p_n = \left[\frac{\gamma_{m(n)}^i}{\lambda} - \frac{N_0B/N}{|h_{m(n),n}|^2\beta}\right]^+$, $\forall n$;

(3) Update the LTE-U UE's throughput
$R_k'^\mathrm{L} = \frac{B}{N}\sum_{n=1}^{N} x_{k,n}\log_2\left(1 + \frac{\beta p_n|h_{k,n}|^2}{N_0B/N}\right)$, $\forall k$;

(4) Update γ_k^i with a step size $\mu \in (0,1)$
$\gamma_k^{i+1} \leftarrow (1-\mu)\gamma_k^i + \mu U'\left(R_k'^\mathrm{L}\right)$.

- When the power allocation to each subcarrier is fixed, the subcarrier assignment scheme can be solved via a simple gradient scheduling algorithm using the following optimal condition:

$$m(n) = \arg\max_k\{U'\left(R_k^\mathrm{L}\right)c_{k,n}\} \tag{13}$$

  where $m(n)$ is the index of UE that subcarrier n should be allocated to and $U'\left(R_k^\mathrm{L}\right)$ is the derivative of utility function about R_k^L.
- When the subcarrier assignment scheme is fixed, the optimal power allocation can be obtained based on the utility-based water-filling [19]

$$\begin{cases} p_n = \left[\dfrac{U'\left(R_{m(n)}^\mathrm{L}\right)}{\lambda} - \dfrac{N_0B/N}{|h_{m(n),n}|^2\beta}\right]^+, \quad \forall n \\ \sum_{n=1}^{N} p_n = P_\mathrm{total} \end{cases} \tag{14}$$

  where $[a]^+ = \max\{a, 0\}$.

Based on the two aforesaid optimal conditions, we can update the marginal utility via the combination of iterative subcarrier assignment and power allocation. The detailed procedure is referred in Algorithm 1. The threshold ε provides a stopping criterion for the iteration and the update step μ decides both the speed and the accuracy of the resource allocation scheme. Notice that a large μ will lead to a faster but inaccurate result while a small μ makes the result more accurate but at a lower convergence speed.

IV. THEORETICAL MODELING OF THE COEXISTENCE MECHANISM

The most important part in OP2 is obtaining the feasible region of $(t_\mathrm{W}, t_\mathrm{L})$, which depends on the neighboring Wi-Fi STAs' states and the MAC configuration of the

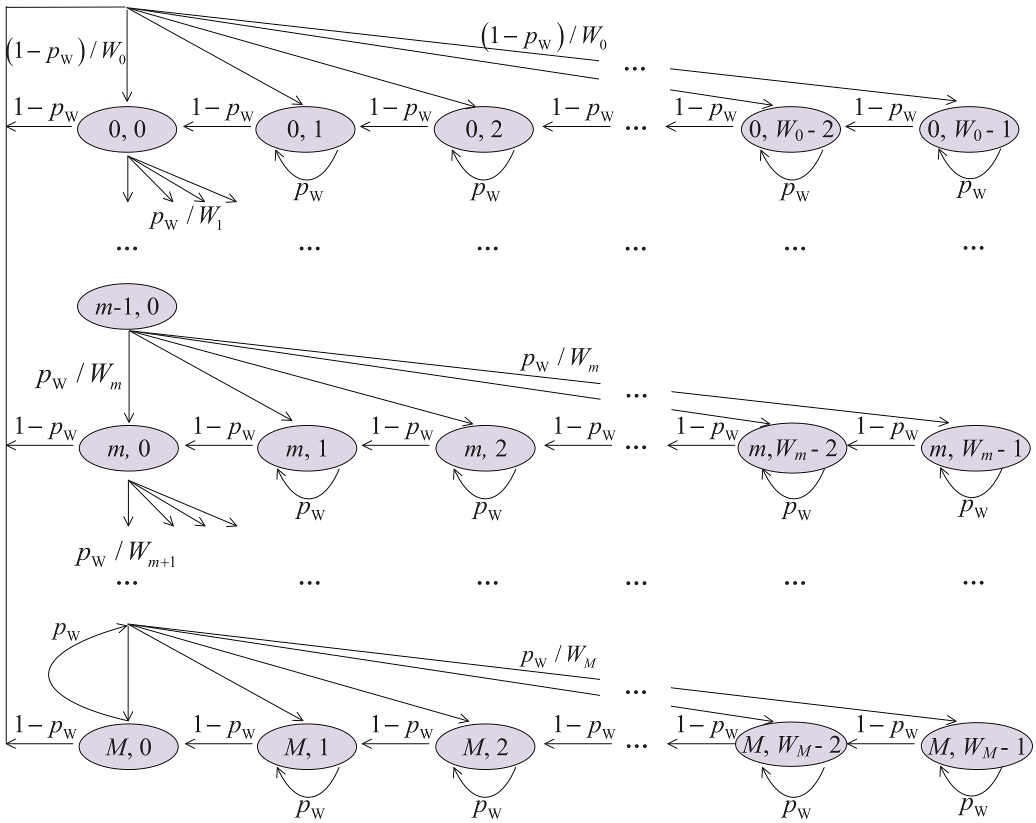

FIGURE 3. Markov model of a Wi-Fi STA with IEEE 802.11 DCF when coexisting with LTE-U network.

LTE-U network. Normally, the number of the MAC configurations of the LTE-U network is limited and thus we can calculate what the value of (t_W, t_L) is when any specific configuration is given, and then traverse all pairs to maximize the objective function in OP2. Over the unlicensed channel, Wi-Fi STAs conform to the fundamental random access mechanism, which is called distributed coordination function (DCF), including the basic access and request-to-send/clear-to-send (RTS/CTS) access. A large volume of existing works have evaluated the performance of the IEEE 802.11 DCF from an analytical perspective. By exploiting the symmetrical characteristic of all the STAs in the network, a relationship between the transmission probability of a nonspecific STA and the network state is established to analyze the IEEE 802.11 DCF throughput via a slotted Markov model in [20]. However, the introduction of the LTE-U with a dissimilar access mechanism will break the homogeneous nature of the network, making the analysis challenging. In the following, by considering an LTE-U BS adopting an LBT-based channel access scheme, we propose a novel Markov model to analyze the interaction between the LTE-U and the Wi-Fi networks to obtain the feasible region $\mathcal{A}$ of (t_L, t_W), which will be integrated into our aforementioned optimization framework to further verify its performance.

A. DCF BEHAVIOR OF Wi-Fi STAs

The potential collision caused by LTE-U's transmissions will make the model of Wi-Fi STAs with coexisting LTE-U different from that with only coexisting Wi-Fi STAs. Any Wi-Fi STA with packets to send will monitor channel activity persistently. If the channel is available for a period of time called distributed interframe space (DIFS), the STA accesses the medium and sends the packet directly. Otherwise, to decrease the collision probability with other potential transmitters (from Wi-Fi or LTE-U network), the STA generates a random integer between 0 to the initial contention window W_0 as the backoff counter. During each slot with length σ specified by the IEEE 802.11 protocol, the STA monitors the channel and decreases the backoff counter by one if the channel keeps idle in this slot. Otherwise if the channel is busy due to the transmission of other STAs or the occupation of the LTE-U network, the backoff procedure is frozen and will be resumed only when the channel is sensed idle again for a DIFS. Once the backoff counter is decremented to zero, the STA will send its packet immediately, however with a potential risk of collision with other transmitters from the Wi-Fi or LTE-U network. After each unsuccessful transmission, the contention window doubles until a maximum value is reached and a new backoff counter will be generated accordingly. Once the STA transmits successfully, the contention window will be reset as the initial value, i.e., W_0.

Based on the above description of DCF mechanism when coexisting with LTE-U, we can construct a revised Markov chain similar to the one proposed in [20] to model the backoff procedure of any unspecific Wi-Fi STA with saturated traffic. As shown in Fig. 3, the STA's state is denoted as (m, b), where m represents the backoff stage, i.e., the number of the STA's retransmission attempts for the present packet and b is the present backoff time counter. A key approximation we make is that, at each transmission attempt, and regardless of the number of retransmissions suffered and the current backoff counter, each packet of Wi-Fi STAs collides with a constant and independent probability p_{W}. Therefore, the STA with any state of $b > 0$ always stays in the same state with a probability p_{W}, representing its backoff is frozen due to the busy channel detected. On the contrary, the STA's backoff counter can be decremented by 1 with probability $1 - p_{\mathrm{W}}$, which means the channel is idle. When the backoff counter is decremented to zero, i.e., the state is $(m, 0)$, the STA will send its packet immediately. Then, the STA's state will transit into $(0, b)$ with probability $(1 - p_{\mathrm{W}})/W_0$, which means that a successful transmission makes the backoff stage reset to 0 and a new backoff counter is uniformly chosen in the range $[0, W_0 - 1]$. However, if a collision happens, the STA's state will transit into $(m+1, b)$ with probability p_{W}/W_{m+1} because of the increased backoff stage and the doubled contention window. In addition, it should be noticed that the backoff stage will not exceed the maximum limitation M. Therefore, the one-step transition probabilities are given by

$$\begin{cases} P(m, b|m, b) = p_{\mathrm{W}} & b \in [0, W_m - 1]\,, m \in [0, M] \\ P(m, b|m, b+1) & \\ \quad = 1 - p_{\mathrm{W}} & b \in [0, W_m - 2]\,, m \in [0, M] \\ P(0, b|m, 0) = \dfrac{1 - p_{\mathrm{W}}}{W_0} & b \in [0, W_0 - 1]\,, m \in [0, M] \\ P(m, b|m-1, 0) = \dfrac{p_{\mathrm{W}}}{W_m} & b \in [0, W_m - 1]\,, m \in [1, M] \\ P(M, b|M, 0) = p_{\mathrm{W}}/W_M & b \in [0, W_M - 1]\,. \end{cases} \tag{15}$$

It should be noted that the biggest difference between the transition of this work and that in [20] is that here p_{W} even includes the collision probability of both Wi-Fi STA and LTE-U BS. Besides, we add the transition from one state to itself, meaning that the sensing result in the slot is busy, which has been considered in [21] as well. If we denote $q_{m,b}$ as the steady probability of state (m, b), based on the Markov states' transitions, we can derive the probability that the STA will transmit its packet via adding the steady probability of all the states with $(m, 0)$ $(m \in [0, M])$ as

$$\begin{aligned} \tau_{\mathrm{W}} &= \sum_{m=0}^{M} q_{m,0} \\ &= \frac{2(1 - 2p_{\mathrm{W}})(1 - p_{\mathrm{W}})}{(1 - 2p_{\mathrm{W}})(W_0 + 1) + p_{\mathrm{W}} W_0 (1 - (2p_{\mathrm{W}})^M)} \end{aligned} \tag{16}$$

where the derivation of p_{W} will be presented in Section IV-C.

B. LBT MECHANISM of LTE-U BS

As shown in Fig. 4(a), we assume the channel occupation of the LTE-U network is initiated by the LTE-U BS via the following LBT method. The sensing of the LTE-U BS is frozen when the channel is busy or announced to be busy by RTS and CTS messages. Only after sensing the channel is idle for a fixed sensing window, i.e., H continuous slots, the LTE-U BS will try to access the unlicensed band. Once successfully accessed, it will occupy it for a length of a wireless frame T_{L} (which is assumed equal to that in original LTE network, i.e., 10ms).

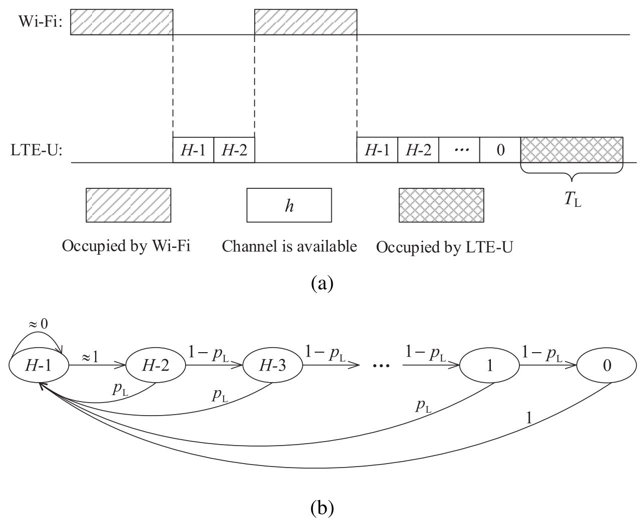

FIGURE 4. **The LBT mechanism of LTE-U and its Markov model. (a) Procedure of the LBT in the LTE-U cell. (b) The Markov model for the LBT-enabled LTE-U BS when coexisting with Wi-Fi network.**

For this LBT scheme, we model the LTE-U network as the Markov chain shown in Fig. 4(b), where the states in circle represent the remaining backoff counter of the LTE-U BS, ranging from 0 to $H - 1$. Different from the model for the Wi-Fi network, when the LTE-U BS is in state $H - 1$, it has almost a probability of one to find an idle channel. This is because that in the scenario of interest, the state of the Wi-Fi network in the previous slot must be in data transmission (either with or without collision) and a busy channel appears in this slot only if the Wi-Fi STA(s) transmitted in the previous slot transmits again, which is of very small probability. However, similar to the model for the Wi-Fi network, for other states of the LTE-U BS, we assume that the LTE-U BS finds a busy channel with a homogeneous probability p_{L}. Finally, if the LTE-U BS finds an idle channel in state 0, it accesses channel for data transmission and then transits into state $H - 1$ to wait for its next channel access chance. Let q_h denote the the steady probability of state h. According to the aforesaid procedures and state transitions, q_h should satisfy the following conditions:

$$\begin{cases} (1-p_L)q_h = q_{h-1}, & h \in \{1,2,3,\ldots,H-2\} \\ \sum_{h=0}^{H-1} q_h = 1 \\ q_{H-1} = q_{H-2}. \end{cases} \tag{17}$$

From (17), we can obtain the probability that the LTE-U BS tries to transmit its packet as

$$\tau_L = q_0 = \frac{(1-p_L)^{H-2}(p_L)}{1+p_L-(1-p_L)^{H-1}} \tag{18}$$

and

$$q_h = q_0 (1-p_L)^h, \quad h \in \{1,2,\ldots,H-2\}. \tag{19}$$

Thus, we can derive the probability that the LTE-U BS occupies the channel when we have the knowledge of collision probability p_L, which is to be derived based on the interaction analysis in the following subsection.

C. INTERACTION OF LTE-U AND Wi-Fi NETWORKS

Although we have constructed two Markov models for Wi-Fi and LTE-U networks, respectively, the mathematical representation for the interaction is still not specified, making the analytical framework unsolved. However, the parameters of the two networks are correlated. From the Wi-Fi network's perspective, the collision probability is related to the probability of collision with other Wi-Fi STAs and with the LTE-U BS, and it is given by

$$p_W = 1-(1-\tau_W)^{K_W-1}(1-p_W^L) \tag{20}$$

where p_W^L is the probability that the Wi-Fi STA collides with the LTE-U BS. In (20), the second term denotes the probability that the Wi-Fi STA's transmission does not collide with any other Wi-Fi STA and LTE-U BS, i.e., all the other Wi-Fi STAs do not transmit any packet and it will not collide with the LTE-U BS. From the LTE-U network's perspective, the probability that the channel is idle is equivalent to the probability that the channel is observed to be idle by the LTE-U BS in each backoff state as follows:

$$(1-\tau_W)^{K_W} = \sum_{h=0}^{H-2} q_h(1-p_L) + q_{H-1}. \tag{21}$$

Finally, the probability that a Wi-Fi STA collides with the LTE-U BS can be derived as a function of conditional probability. We define two events related to one specific Wi-Fi STA: A_1 represents the event that a Wi-Fi STA and the LTE-U occupy the channel in the same time slot and A_2 represents the event that a Wi-Fi STA occupies the channel in a time slot. As a result, we have

$$\begin{aligned} p_W^L &= P(A_1|A_2) = \frac{P(A_1A_2)}{P(A_2)} = \frac{\tau_L p_L \frac{\tau_W}{1-(1-\tau_W)^{K_W}}}{\tau_W} \\ &= \frac{\tau_L p_L}{1-(1-\tau_W)^{K_W}}. \end{aligned} \tag{22}$$

Using (16), (18), (20)-(22), we can jointly solve τ_W, p_W, p_W^L, τ_L, and p_L via numerical techniques. To evaluate the performance of the coexistence network, we need to analyze what will happen in a random slot. According to the occupant of the channel, we can divide the coexistence scenario into four cases:

1) The channel is idle and all the Wi-Fi STAs and the LTE-U BS are sensing the channel. The probability that the channel is in this state is given by

$$\begin{aligned} P_{\text{Idle}} &= 1 - P_{\text{Tr}} \\ &= 1-\tau_L-\left[1-\tau_L-\tau_L/(1-p_L)^{H-2}\right]p_L \end{aligned} \tag{23}$$

where P_{Tr} is the probability that at least one Wi-Fi STA or the LTE-U BS is occupying the channel. The last term of the second equality calculates the probability that the LTE-U is sensing and one or more Wi-Fi STAs are transmitting packet(s). The duration of this situation is σ which is the length of the sensing slot.

2) The channel is only occupied by one Wi-Fi STA. The probability that the channel is in this state is given by

$$P_W = K_W\tau_W(1-\tau_W)^{K_W-1}(1-p_W^L). \tag{24}$$

The duration of this situation is specified by the IEEE 802.11 protocol, and is given by

$$\begin{aligned} T_W = {} & T_{\text{RTS}} + 3T_{\text{SIFS}} + 4\delta + T_{\text{CTS}} + T_{\text{Header}} \\ & + T_{\text{ACK}} + T_{\text{DIFS}} + T_P \end{aligned} \tag{25}$$

where T_{RTS}, T_{CTS}, T_{Header}, T_{ACK}, and T_P are time durations of transmitting RTS packet, CTS packet, the PHY layer header, and the data packet, respectively; T_{SIFS} and T_{DIFS} are the length of short interframe space and DIFS, respectively; and δ is the propagation delay.

3) The channel is only occupied by the LTE-U BS. The probability that the channel is in this state is given by

$$P_L = \tau_L(1-p_L). \tag{26}$$

The duration of this situation is T_L.

4) A collision happens. The probability that the channel is in this state is given by

$$P_C = P_{\text{Tr}} - P_W - P_L. \tag{27}$$

We assume that the LTE-U BS can sense the collision immediately so that the duration of this situation is as long as that in Wi-Fi networks, denoted by

$$T_C = T_{\text{RTS}} + T_{\text{DIFS}} + \delta. \tag{28}$$

Using the above results, we can obtain the successful occupation ratio of Wi-Fi network and that of LTE-U network as follows:

$$t_W = \frac{P_W T_P}{P_W T_w + P_L T_L + P_C T_C + (1-P_{\text{Tr}})\sigma} \tag{29}$$

$$t_L = \frac{P_L T_L}{P_W T_w + P_L T_L + P_C T_C + (1-P_{\text{Tr}})\sigma} \tag{30}$$

where only the time ratio for transmitting useful packets is considered in (29).

Therefore, if we have configuration parameters of the LTE-U BS's access mechanism, i.e., H and T_L, we can calculate the two networks' occupation time ratio, t_W and t_L, using (29) and (30). Normally, the available configuration parameters are limited, we can get the optimal configuration via an exhaustive search to maximize the utility defined in OP2.

TABLE 1. Key parameters of IEEE 802.11ac protocol.

Symbol	Description	Value
W_0	Initial backoff window size	16
M	Maximal backoff stage	6
σ	Length of a sensing slot	9 μs
T_{DIFS}	Length of a DIFS	34 μs
T_{RTS}	Length of an RTS frame	80 μs
T_{CTS}	Length of a CTS frame	73 μs
T_{ACK}	Length of an ACK frame	72 μs
T_{SIFS}	Length of an SIFS	16 μs
T_{Header}	Length of a PHYHeader	52 μs
T_{P}	Length of a packet	5484 μs

V. NUMERICAL RESULTS

In this section, we first perform simulations to verify our analytical results and then investigate the performance of our proposed proportional fairness-based resource allocation scheme. Suppose that in a square with size 60m×60m a Wi-Fi network consisting of four STAs is coexisting over a 20MHz channel with an LTE-U network, in which a BS located at (30m, 30m) is serving four UEs. All STAs and UEs are randomly deployed as a fixed network topology. The Wi-Fi network is working with the IEEE 802.11ac protocol whose details are listed in Table 1. The LTE-U network is operating with the aforementioned LBT-based channel access scheme. The total number of subcarriers which the LTE-U BS transmits over is set to 1200 and each subcarrier has a bandwidth of 15kHz. Both the Wi-Fi STAs and the LTE-U BS transmit with a maximal power constraint of 15dBm and the noise power at any receiver is assumed as −90dBm. For the channel model, we consider the small-scale Rayleigh fading and the path-loss model [13] as follows:

$$\text{PL} = 38.46 + 20\log_{10}(R) + 0.7R \tag{31}$$

where R is the distance between the transmitter and the receiver. The acceptable BER is set as 10^{-6} for rate adaptation. For the utility function, in the simulation we use natural logarithm function.

Figure 5 shows the relationship between the fixed sensing window H of the LTE-U BS and the time occupation ratio of both networks. It can be observed that the larger the fixed sensing window of the LTE-U BS, the larger the occupation ratio of the Wi-Fi network and, accordingly, the smaller the occupation ratio of the LTE-U network, implying that the LTE-U network is sharing the unlicensed channel in a more conservative manner. As an intruder in the unlicensed band, the LTE-U BS must achieve a performance balance between the Wi-Fi network and the LTE-U network. Furthermore, the

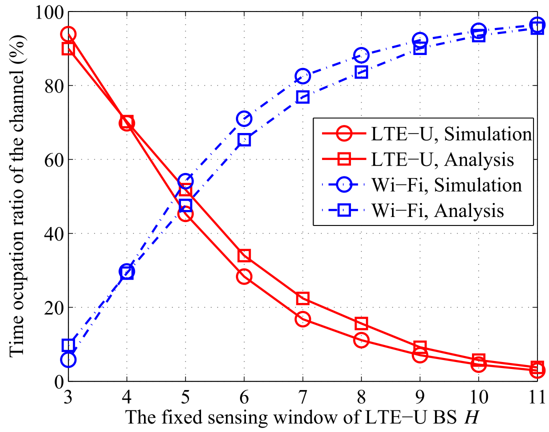

FIGURE 5. Comparison of the analytical and simulated time occupation ratio.

analytical results approach the simulation results with only minor differences. The deviation between the analysis and the simulation results mainly arises from the approximation of the fixed transition from state $H-1$ to state $H-2$ for the LTE-U BS (see Fig. 4(b)).

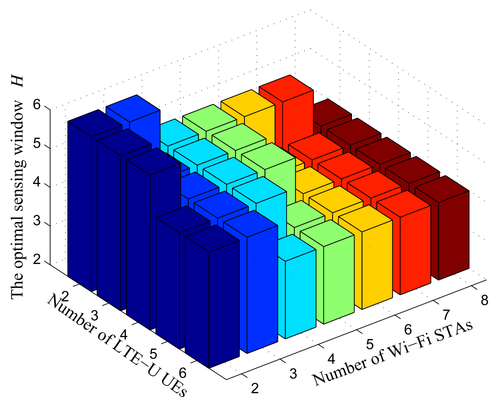

FIGURE 6. The optimal sensing window with various number of LTE-U UEs and Wi-Fi STAs.

Therefore, with a simple exhaustive search, the analytical results can be well exploited to solve OP2 to find the optimal sensing window of the LTE-U network, which generates the best MAC-layer device number-weighted spectrum occupation time-oriented PF. Based on this, in Fig. 6 we show the distribution of the optimal sensing window length H with different number of LTE-U UEs and Wi-Fi STAs when weighting factor α is fixed as 0.5. We can see that when the number of Wi-Fi STAs is fixed, the more the LTE-U UEs are, the smaller the sensing window should be. It is because that when the number of LTE-U UEs increases, the LTE-U BS should have a higher channel occupation ratio to achieve the proportional fairness. Similarly, when the number of Wi-Fi STAs increases, the contention-based channel sharing scheme among the Wi-Fi STAs and the LTE-U BS will make the channel occupation ratio of LTE-U smaller, and thus the sensing window should also be decreased to drive the LTE-U BS to access the channel more frequently.

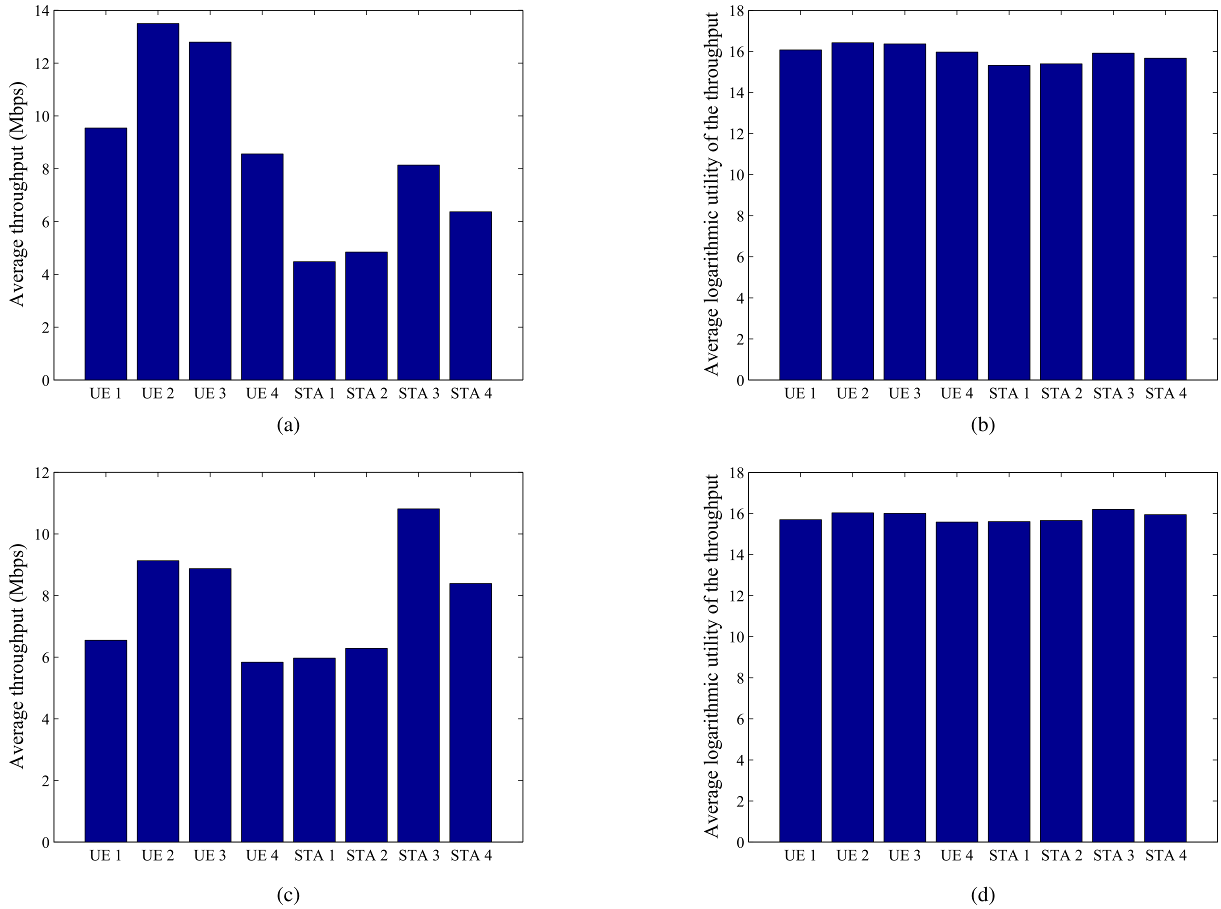

FIGURE 7. The throughput and logarithmic utility of the two coexisting networks with the proposed proportional fairness-based resource allocation scheme. (a) Throughput when $\alpha = 0.5$. (b) Logarithmic utility when $\alpha = 0.5$. (c) Throughput when $\alpha = 0.3$. (d) Logarithmic utility when $\alpha = 0.3$.

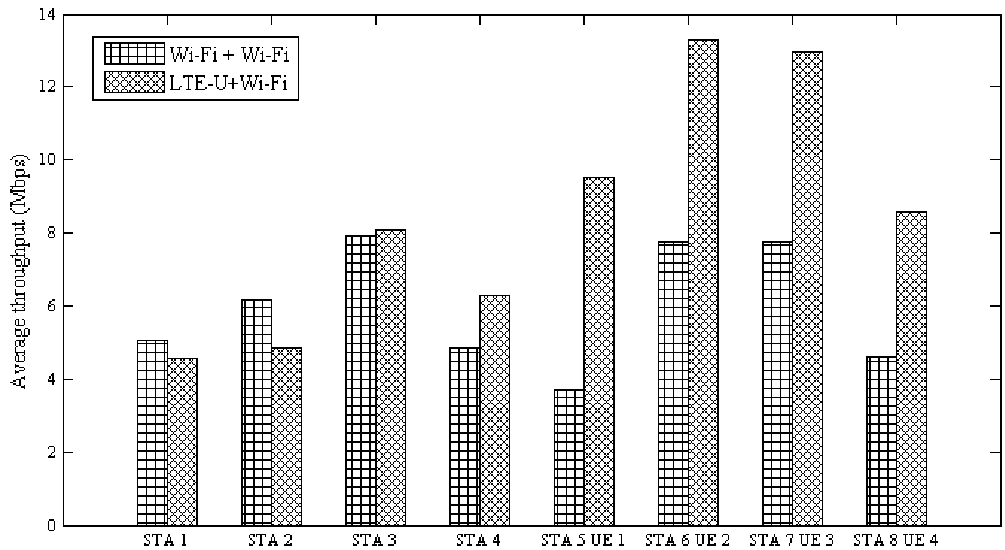

FIGURE 8. Throughput comparison of the Wi-Fi+Wi-Fi and LTE-U+Wi-Fi coexistence.

According to the results in Figs. 5 and 6, we find that given weighting factor $\alpha = 0.5$ (i.e., assigning the same weight to both networks), the optimal sensing window of the LTE-U BS should be 5, offering each type of networks almost a half chance of collision-free channel access. However, it is noticed in Figs. 7(a) and 7(b) that when $\alpha = 0.5$, although all the devices (including Wi-Fi STAs and LTE-U UEs) have very close utilities, the average throughput of LTE-U UEs is still much higher than that of the Wi-Fi STAs, due to the more advanced centralized channel-aware scheduling technique. Therefore, a higher weight for the Wi-Fi network is potentially needed in future coexistence scenario. Taking this into consideration, we also study the results of different α's. By setting $\alpha = 0.3$, as shown in Figs. 7(c) and 7(d) the performance gap between LTE-U UEs and Wi-Fi STAs further shrunk because the adjusted chances of collision-free channel access for both networks. The Jain's fairness index [22] is respectively calculated as 0.9359 in the first case and 0.9551 in the second case, which shows that the allocation result of $\alpha = 0.3$ is much fairer than that of $\alpha = 0.5$. In this case, the optimal sensing window of LTE-U BS increases to 6, and thus the Wi-Fi network gains extra time occupation ratio as compared to $\alpha = 0.5$.

In Fig. 8, we substitute all the LTE-U UEs with Wi-Fi STAs in the same locations and compare all the devices' throughput in this two different scenarios. The results show that as compared with the coexistence among only Wi-Fi STAs, applying our proposed scheme the LTE-U networks will have little impact on the Wi-Fi STAs but the LTE-U network has a much higher transmission efficiency which validates the advantages of LTE-U technology.

VI. CONCLUSION

In this paper, we have investigated the proportional fairness-based resource allocation in the coexistence between LTE-U and Wi-Fi networks. An analytical framework has been proposed to decouple the cross-layer optimization problem into two subproblems, which can be solved in the MAC layer and the physical layer independently. To fulfil the practical implementation of this algorithms, we further propose an LBT-based channel access scheme for the LTE-U network and give an analysis method for the coexistence performance about channel occupation ratio. The analytical results and the performance of the resource allocation algorithm are both validated by numerical simulations. In our future work, we will study the performance of coexisting LTE-U and WiFi in a more complicated network scenario including hidden/exposed terminal problem, the effect of the user actions' prediction, and the derivation of the Wi-Fi networks' information.

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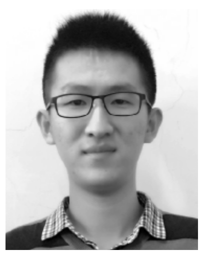

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