Adaptive Resource Allocation for LTE/WiFi Coexistence in the Unlicensed Spectrum

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***Abstract*—Unlicensed spectrum, unlike its licensed counterpart, has to be shared by multiple technologies and hence the performance is heavily impacted by cross-technology interference. In this paper, we focus on the coexistence mechanism of LTE and WiFi in the unlicensed spectrum. We first develop a simple yet effective model for the LTE-U throughput analysis, and then propose a fair coexistence criterion and design the duty cycle allocation that optimizes the Carrier Sensing Adoptive Transmission (CSAT) mechanism for LTE-U/WiFi. Furthermore, we design a Throughput Optimal Channel Selection (TOCS) algorithm for LTE-U devices to achieve optimal channel allocation. Simulation results demonstrate that the new methods can improve the total system throughput while guaranteeing fairness between LTE-U and WiFi, which is critical to the adoption of LTE in the unlicensed spectrum.**

***Index Terms*—LTE in unlicensed spectrum (LTE-U); WiFi; Coexistence**

I. Introduction

With the exponential growth of smart mobile devices, meeting the enormous traffic demand has become one of the most critical issues in today's wireless networks. Despite the significant progress over the last decade, the Long Term Evolution (LTE) system has become increasingly limited by the crowded *licensed* spectrum. In order to improve the capacity, the Third Generation Partnership Project (3GPP) standard group is actively seeking for advanced solutions to boost the network capacity while providing better user experience to customers. As an important effort, operators and standard bodies are actively seeking to extend the LTE operation into the *unlicensed* spectrum, which is referred to as LTE in Unlicensed spectrum (LTE-U) [1]. This is an attractive choice mostly thanks to the availability of large bandwidth in the 2.4GHz and 5GHz bands [2].

In reality, WiFi technology has already been widely deployed and hence become the *de facto* access technology in the unlicensed spectrum. As a result, the LTE-U solution must be compatible with existing WiFi devices to ensure fair sharing of the spectrum. However, unlike the traditional LTE system where base stations are managed by one operator, coordination is difficult for unlicensed networks of different WiFi and LTE-U stations. Due to the fundamental differences in the physical layer and Media Access Control (MAC) layer design of LTE and WiFi, a direct implementation of LTE in the unlicensed spectrum may impact the opportunistic channel occupancy of co-channel WiFi, especially in high load scenarios. In [3], an experimental analysis for indoor deployment shows that the performance of WiFi would decrease rapidly in the presence of LTE-U, mainly due to the aggressiveness of LTE channel access. These challenges have recently attracted much attention from both academia and industry, and some studies have been reported in the literature. In [4], the authors evaluate the coexistence performance between LTE-U and Wi-Fi systems, and summarize some challenges faced by both technologies. In [5], Qualcomm presents an effective channel selection policy based on interference levels. If the interference of the occupied channel exceeds a certain level, LTE-U switches to a new channel which is measured both before and during the operation. Furthermore, [5] shows that with the proposed coexistence solution, adding a neighboring LTE-U base station does not affect any existing WiFi node more than adding another WiFi access point (AP). As a result, they argue that LTE-U protects WiFi better than WiFi protects itself. In [6], the authors design a second-price reverse auction mechanism, which enables the LTE provider and the WiFi APs to effectively negotiate the operation mode. In [1], the authors discuss the major challenges for the LTE/WiFi coexistence. They introduce regulations, principles and typical deployment scenarios of LTE-U.

The main contributions of this paper are three-fold. First, we introduce a simple yet effective analytical model for LTE-U and WiFi coexistence, which balances tractability and usefulness. Second, based on the analytical model and a fair coexistence criterion, we propose the Proportion-Adaptive Allocation (PAA) principle, which is an optimal duty cycle allocation solution to share *time* resources in CSAT. Finally, we propose a Throughput Optimal Channel Selection

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(TOCS) algorithm for the LTE-U devices to extend our solution to multiple channels and share *frequency* resources, and improve the overall system-wide performance. We also carry out numerical simulations to validate the theoretical analysis.

The remainder of this paper is organized as follows. In Section II, we describe the LTE-U/WiFi coexistence system. In Section III-A, an analytical mode for the coexistence system is developed. In Section III-B, we present the PAA design to share the unlicensed spectrum in the time domain. In Section IV, the TOCS algorithm is proposed to achieve better performance in a multi-channel scenario. In Section V, we present the simulation results and evaluate the performance of the proposed solutions. Section VI concludes this paper.

II. Network Model and Preliminaries

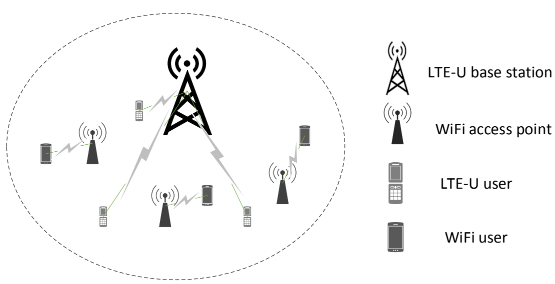

Fig. 1: An exemplary LTE-U/WiFi coexistence network.

We consider a deployment consisting of a LTE-U system and a WiFi system in the unlicensed band, as shown in Fig. 1. There are $N_{\text{lte-u}}$ LTE-U users and N_{wifi} WiFi users in this network. We consider a fully loaded network where all nodes has full-buffered data to transmit. For the WiFi MAC protocol, the channel access mechanism is the well-known Distributed Coordination Function (DCF). It is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. In particular, a WiFi station under DCF operation tries to access the channel with the following procedure: First, a station which has a packet to transmit monitors the channel activity. Then the station will transmit if the channel is detected to be idle for a period of time that equals to a distributed interframe space (DIFS). Otherwise, the station will keep monitoring the channel until it is idle for a DIFS. At this point, the station generates a random backoff interval (if collision has been observed) before transmitting, in order to minimize the probability of collision with packets transmitted by other stations.

The WiFi channel access mechanism is vastly different from LTE, which divides the total available time-frequency resources into Physical Resource Blocks (PRBs) and assigns them to users. Different PRBs can be scheduled to different users in the same subframe, achieving a multi-user diversity gain. A simple and easy-to-manage mechanism, called Carrier Sensing Adoptive Transmission (CSAT), has been proposed by Qualcomm [5] to orthogonalize the time resources between WiFi users and LTE-U users. The basic idea of CSAT is to define a Time Division Multiplexing (TDM) cycle during which the LTE-U transmits in an ON/OFF style, i.e., a fraction of the cycle is used exclusively for cellular transmissions while the rest is left for the transmission of WiFi.

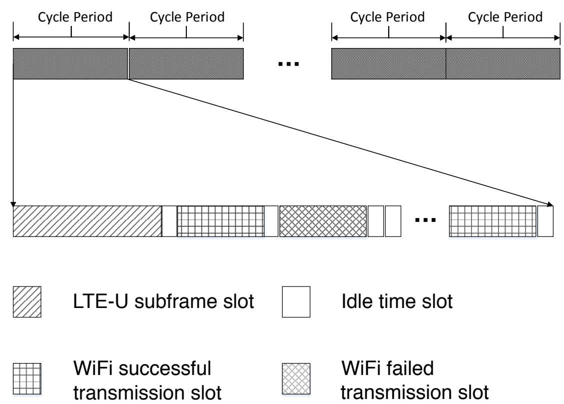

Fig. 2: An illustration of the CSAT duty cycle structure.

In this work we focus on the CSAT mechanism and propose the Proportion-Adaptive Allocation (PAA) principle to optimally coordinate the unlicensed spectrum sharing with WiFi system, as illustrated in Fig. 2. We define T_{period} as a time length of one Cycle Period (CP) which can be set to a few hundreds milliseconds for controlling the data transmission delay. Channel will be occupied by a LTE-U subframe for a certain duration, and then LTE-U keeps silent via the blank subframe technique for the rest of this CP. From Fig. 1, we can see that there may be four types of time slots in a CP: a time slot in which there is an idle duration; a time slot in which there is a successful WiFi packet; a slot in which there is a failed WiFi packet; and a time slot which is occupied by LTE-U. We define $T_{\text{lte-u}}$, T_{idle}, T_{s} and T_{c} as the time length of LTE-U subframe, idle time slot, WiFi successful packet and WiFi failed packet, respectively. Note that the collision between LTE-U and WiFi is ignored, as the overlapping at the boundary is too small to meaningfully impact the network throughput in a CSAT framework. In particular, the network will be a WiFi only system if the cyclic ratio $\alpha \triangleq T_{\text{lte-u}}/T_{\text{period}} = 0$. The cyclic ratio α can be adjusted for better coexistence between LTE and WiFi. Therefore it is important to select an optimal α, which will be addressed in Section III.

We also assume that unlicensed LTE-U control messages are sent via the licensed spectrum (referred to as the "anchor" carrier). Since a user needs to receive control information to locate and decode its data within a LTE-U subframe, it follows that control messages sent over the licensed spectrum for a given subframe must be aligned with the subframe in the unlicensed band where the data is actually transmitted. That is, transmitting the control information through the licensed spectrum means that the unlicensed channel transmissions is synchronized to the subframe boundaries in the licensed band interface.

III. Proportion-Adaptive Allocation

In this section, we first present an analytical model for the LTE-U/WiFi coexistence network described in Section II, and then describe the Proportion-Adaptive Allocation (PAA) principle for LTE-U and WiFi to share the unlicensed spectrum, which computes the optimal ratio between LTE-U and WiFi in CSAT.

A. Throughput Analysis with Coexistence

The coexistence network can be analyzed by exploiting a Discrete Time Markov Chain (DTMC) model developed in [7]. First, we use τ to denote the probability of a WiFi station transmitting in an arbitrarily given time slot. According to [7], τ can be expressed as

$$\tau = \frac{2(1-2p)(1-p)}{(1-2p)(W+1)+pW(1-(2p)^m)}, \tag{1}$$

where W is the size of the minimum Contention Window(CW), m is the maximum backoff stage. Then we can write the probability of a transmitted packet encounters a collision as

$$p = 1-(1-\tau)^{N_{\text{wifi}}-1}. \tag{2}$$

Noting that Eqn. (1) and (2) are too complex to derive an explicit expression, thus we typically need to leverage numerical methods to obtain τ and p.

We denote by $\overline{S_{\text{wifi}}}(N_{\text{wifi}}, \alpha)$ as the WiFi system normalized throughput, which is defined as the fraction of time over which the channel is used to successfully transmit packets. To derive $\overline{S_{\text{wifi}}}$, it is necessary to analyse what will happen in a arbitrarily chosen time slot. For a given WiFi station, there are four type of time slots: idle slot, LTE-U transmission slot, successful WiFi transmission slot, and failed WiFi transmission slot. The probability of each kind of slot is defined as P_{idle}, $P_{\text{lte-u}}$, P_{s}, and P_{c}, respectively. Since there are N_{wifi} WiFi stations and a LTE-U system contending for the channel, and each station transmits independently with probability τ, P_{idle} can be written as

$$P_{\text{idle}} = (1-P_{\text{lte-u}})(1-\tau)^{N_{\text{wifi}}}. \tag{3}$$

On the other hand, P_s is the probability that there is exactly one WiFi station that is actively transmitting, which can be written as

$$P_s = N_{\text{wifi}}\tau(1-\tau)^{N_{\text{wifi}}-1}(1-P_{\text{lte-u}}). \tag{4}$$

Finally, the probability of a failed WiFi transmission can be written as

$$P_c = 1-P_s-P_{\text{idel}}-P_{\text{lte-u}}. \tag{5}$$

Let $E[\text{slot}]$ be the average length of the time slot, which can be written as

$$E[\text{slot}] = P_{\text{idle}}T_{\text{idle}} + P_{\text{lte-u}}T_{\text{lte-u}} + P_{\text{c}}T_{\text{c}} + P_{\text{s}}T_{\text{s}}. \tag{6}$$

As for $P_{\text{lte-u}}$, we known that $\alpha > 0$ means that there is at least one LTE-U subframe within a given PD. Therefore, the $P_{\text{lte-u}}$ can be given by

$$P_{\text{lte-u}} = \begin{cases} \dfrac{E[\text{slot}]}{T_{\text{period}}} & \alpha > 0 \\ 0 & \alpha = 0. \end{cases} \tag{7}$$

Moreover, the average time of successful transmission in an average time slot is $P_{\text{s}}T_{\text{s}}$. We are now able to express $\overline{S_{\text{wifi}}}$ as

$$\overline{S_{\text{wifi}}} = \frac{P_{\text{s}}T_{\text{s}}}{E[\text{slot}]} = \frac{P_{\text{s}}T_{\text{s}}}{P_{\text{idle}}\sigma + P_{\text{lte-u}}T_{\text{lte-u}} + P_{\text{c}}T_{\text{c}} + P_{\text{s}}T_{\text{s}}}. \tag{8}$$

The throughput of WiFi, in an average time slot, can be obtained as

$$S_{\text{wifi}} = \overline{S_{\text{wifi}}}R^*_{\text{wifi}}, \tag{9}$$

where R^*_{wifi} is the rate of WiFi transmission in a successful packet time slot, which can be considered as a constant. Then, we can explicitly state the relationship between the LTE-U/WiFi coexistence system and the WiFi only system as

$$S_{\text{wifi}}(N_{\text{wifi}}, \alpha) = (1-\alpha)S_{\text{wifi}}(N_{\text{wifi}}, 0). \tag{10}$$

Next, we can write the average rate of the individual WiFi station as

$$\begin{aligned} R_{\text{wifi}}(N_{\text{wifi}}, \alpha) &= \frac{S_{\text{wifi}}(N_{\text{wifi}}, \alpha)}{N_{\text{wifi}}} \\ &= (1-\alpha)R_{\text{wifi}}(N_{\text{wifi}}, 0). \end{aligned} \tag{11}$$

As we can see, R_{wifi} is a function that consists of α and N_{wifi}. From the Eqn. (11), we can see that α and N_{wifi} are independent of each other. On the other hand, we can obtain the throughput of LTE-U system, which is given by

$$R_{\text{lte-u}} = \alpha * R^*_{\text{lte-u}}, \tag{12}$$

where $R^*_{\text{lte-u}}$ is the transmission rate of LTE-U, which is considered as a constant.

B. Fair Coexistence Criteria and Optimal Duty Cycle

For the simultaneous operation of LTE-U and WiFi in the same unlicensed spectrum, a fair and reasonable coexistence mechanism is an indispensable requirement. From the aforementioned analytical model, we can see that the duty-cycle coefficient is an important parameter that can be used to balance throughput of LTE-U and WiFi. We thus aim to achieve a time resource allocation scheme that LTE-U can co-exist with WiFi fairly. There are two cases which we need to consider. For the WiFi users, coexistence should ensure that the performance of WiFi does not degrade more than if another WiFi station were added to the

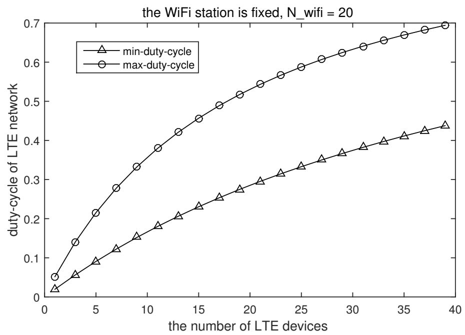

Fig. 3: Max-duty-cycle and Min-duty-cycle

WiFi only network [8]. For the new LTE-U users, its performance should not be lower than the WiFi users[1]. Note that both criteria are meant for the same location. In order to achieve a fair coexistence system, we have the following two constraints that reflect the above ideas.

$$\begin{cases} R_{\text{wifi}}(N_{\text{wifi}}, \alpha) \geq R_{\text{wifi}}(N_{\text{wifi}} + N_{\text{lte-u}}, 0) \\ R_{\text{lte-u}}(N_{\text{wifi}}, \alpha) \geq R_{\text{wifi}}(N_{\text{wifi}}, \alpha), \end{cases} \tag{13}$$

where N_{wifi} and $N_{\text{lte-u}}$ are the number of WiFi stations and LTE devices, respectively. By rewriting Eqn. (13), boundaries of α can be obtained as

$$\begin{cases} \alpha_{min} = \dfrac{1}{1 + \frac{R^*_{\text{lte-u}}/R^*_{\text{wifi}}}{N_{\text{lte-u}} * R_{\text{wifi}}(N_{\text{wifi}}, 0)}} \\ \alpha_{max} = 1 - \dfrac{R_{\text{wifi}}(N_{\text{wifi}} + N_{\text{lte-u}}, 0)}{R_{\text{wifi}}(N_{\text{wifi}}, 0)}. \end{cases} \tag{14}$$

Based on the two constraints above, the optimal duty cycle allocation can be obtained as

$$\alpha^* = f(N_{\text{wifi}}, N_{\text{lte-u}}) = \beta\alpha_{\text{max}} + (1-\beta)\alpha_{\text{min}}, \tag{15}$$

where β is a weight factor whose value can be chosen from $[0, 1]$. How to define a reasonable β to find an optimal performance of a coexistence network is not the focus of this paper and will be explored in the future work.

Fig. 3 depicts the two constraints of α with 20 WiFi stations. It can be seen that with the added LTE-U devices, the two constraint boundaries will increase. This is because that with the fairness principle, time resource will be allocated more in high LTE-U devices density deploy.

IV. Multi-Channel LTE-U Device Allocation

In this section, we attempt to extend PAA to a *multi-channel* scenario. First, we consider a coexistence network in the unlicensed spectrum, where there are both LTE-U devices and WiFi stations. The number of available channels for LTE-U and WiFi is denoted as c.

[1]Otherwise they should use WiFi as the access technology, not LTE-U.

The number of WiFi stations corresponding to channel i is denoted as n_i. There are M LTE-U devices which we will allocate to different channels. The amount of LTE-U devices corresponding to channel i is defined as m_i. It is assumed that one LTE-U device can only occupy one channel.

According to the channel selection principle proposed in [5], LTE-U operators should select the best channel to contend with WiFi stations. However this may allocate many users, including WiFi stations and LTE-U devices , to one channel. Meanwhile, other channels may be occupied by few users. We intend to propose a new allocation scheme that can balance the load among channels to improve total channel utilization.

In order to achieve the highest aggregated throughput of LTE-U, we need to solve the following optimization problem

$$\max_{m_i..m_c} \quad \sum_{i=1}^{i=c} \alpha_i^* R_{\text{lte}} \tag{16}$$

$$s.t. \quad \alpha_i^* = f(n_i, m_i) \qquad i = 1...c \tag{17}$$

$$\sum_{i=1}^{i=c} m_i = M \tag{18}$$

$$m_i \in \mathbb{N} \qquad i = 1...c, \tag{19}$$

where α_i^* is denoted as the LTE-U duty cycle coefficient corresponding to channel i based on constraint (17), when the PAA algorithm is adopted. Constraint (18) specifies the fact that M LTE-U devices must be allocated to c channels. Objective (16) maximizes the total throughput of LTE-U devices in all unlicensed channels.

On the surface, this problem is a mixed integer nonlinear optimization problem (MINLP), which is NP hard. However, for this particular problem, we propose a Throughput Optimal Channel Selection (TOCS) algorithm for LTE-U devices in Algorithm 1, and prove its optimality. The key idea of TOCS is that a new LTE-U device will select an optimal channel based on the *original* allocation of the LTE-U devices.

Algorithm 1 The TOCS algorithm

Set $m_j = 0$, $t_j = 0$, $\forall j = 1, \cdots, c$
for $i = 1$; $i < M$; $i = i + 1$ **do**
  for $j = 1$; $j < c$; $j = j + 1$ **do**
    $temp_j = f(n_i, m_i + 1)$
    $S_j = 1 - \sum_{i=1, i \neq j}^{c} t_i + temp_j$
  end for
  $z = \arg\max(S)$
  $t_z = temp_z$
  $m_z = m_z + 1$
end for
Return: $m_1, m_2, \cdots, m_c$

Theorem 1. *The TOCS algorithm solves the optimization problem described in* (16) *to* (19).

Proof. Let TOCS be the solution output by the algorithm and O be the optimal solution. The proof idea is to gradually modify O but preserve its optimality at each step, until we have a solution identical to the solution $TOCS$ found by the TOCS algorithm.

We denote that

- $O(k-1) = \{m_1^{k-1}, ...m_i^{k-1}, m_j^{k-1}, ...m_c^{k-1}\}$,
- $O(k) = \{m_1^{k}, ...m_i^{k}, m_j^{k}, ...m_c^{k}\}$,
- $\mathsf{TOCS}(k) = \{m_1^{k-1}, ...m_i^{k-1} + 1, m_j^{k-1}, ...m_c^{k-1}\}$,

where $O(k-1)$ and $O(k)$ are the optimal solutions with $n = k-1$ and $n = k$ LTE-U devices, respectively. According to the TOCS algorithm, we will have the solution $\mathsf{TOCS}(k)$ if channel i is optimal for step k selection. Let $B(\cdot)$ be the aggregated throughput of LTE-U system in multi-channel scenario. We aim to maximize the $B(\cdot)$ by selecting the optimal solution allocation.

Let $\alpha_i^*(m_i)$ denote the fraction of time resource which LTE-U system use in channel i with m_i LTE-U devices. Based on Eqn. (17), we have the following relationship for $k-1$ devices:

$$\begin{aligned} &\alpha_i^*(m_i^{k-1} - P - 1) + \alpha_i^*(m_i^{k-1} + Q + 1) \\ &\leq \alpha_j^*(m_j^{k-1} - P) + \alpha_j^*(m_j^{k-1} + Q), \end{aligned} \tag{20}$$

where P and Q are integers which are larger than 1. The combination of m_i^k and m_j^k can be replaced by $m_i^k - 1$ and $m_j^k + 1$, if the allocation satisfies Eqn. (20). Moreover we know that $B(O(k)) \leq B(O^{'}(k))$. Thus, this exchange will not decrease the total throughput of LTE-U. By repeating this argument and noting that $O(k)$ is the optimal solution and $B(O(k)) \leq B(\mathsf{TOCS}(k))$, the proof is complete. $\square$

V. Simulation Results

In this section, we evaluate the performance of the proposed solution in both single and multi-channel scenarios through numerical simulations. We set W and m to be 32 and 5, respectively. The MAC and physical layer header sizes are 272 and 128 bits, respectively. The acknowledgement packet and payload sizes are set to 240 and 8184 bits, respectively. The transmission rates of WiFi and LTE-U are assumed to be 50 and 100 Mbps, respectively. SIFS and DIFS are set to 28 and 128 us, respectively. One idle time slot is set as 1 us.

For evaluation, we compare the optimal duty cycle allocation algorithm for CSAT and the straightforward CSMA/CA mechanism where 20 LTE-U devices and 20 WiFi stations occupy the same unlicensed spectrum. Fig. 4 shows the throughput of coexistence with traditional CSMA/CA mechanism and the proposed mechanism with different weight factors, respectively. It is seen that with an increasing weight factor, the throughput of WiFi system will decrease and approach the value with equal throughput of WiFi system in

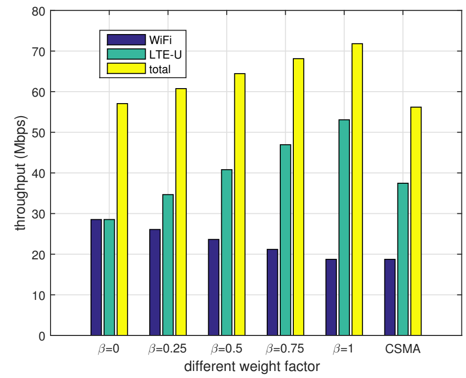

Fig. 4: Performance evaluation with different parameters.

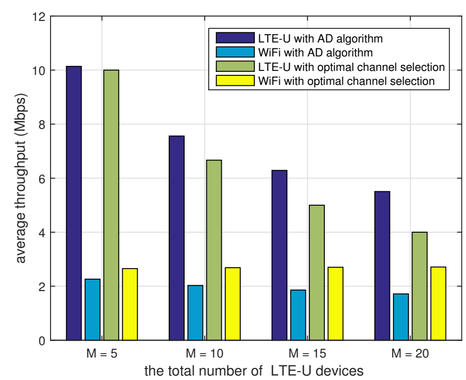

Fig. 5: Performance comparison with channel selection.

with CSMA/CA . In contrast, the throughput of LTE-U system which adopts the optimal duty cycle will increase with an increasing weight factor. This is because that with the increasing weight factor, the proposed allocation can improve the channel utilization.

Then, we compare the proposed TOCS algorithm and the channel selection mechanism in a multi-channel scenario. We assume that the WiFi station distribution in different channels is $[5, 15, 25]$. There are four cases used to evaluate the performance of different channel selection mechanisms. Fig. 5 shows the average user throughput of WiFi and LTE-U with the proposed TOCS method and the optimal channel select scheme, respectively. With the increased number of LTE-U devices, the average throughput of LTE-U users decreases more slowly than the optimal channel select scheme. This is because our method has higher spectrum utilization than simply selecting an optimal channel.

VI. Conclusion

In this paper, we have enhanced the CSAT mechanism which allows LTE-U to co-exist with WiFi in the unlicensed spectrum. Building on fair coexistence criteria that (1) LTE-U should not degrade the throughput of existing WiFi stations more than introducing another WiFi, and (2) LTE-U should not have lower throughput than another WiFi, the gain of the proposed PAA algorithm comes from an optimization of the duty cycle between LTE and WiFi, taking into account the different access protocols of these technologies and their throughput models. We then extend PAA to a multi-channel deployment, where LTE-U needs to decide how to allocate different devices to different channels. A greedy TOCS algorithm is developed to obtain the optimal device allocation on different channels. Simulation results show that the new methods significantly improve the overall system performance than naive CSAT.

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