Methods for the Allocation of Almost Blank Subframes with Fixed Duty Cycle for Improved LTE-U/Wi-Fi Coexistence

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***Abstract*—In order to cope with the increased demand of wireless services and applications, LTE over unlicensed spectrum has been proposed to extend the operation of LTE to operate also over unlicensed bands. However, this extension faces various challenges regarding the coexistence between LTE-U and different technologies that use these unlicensed spectrum bands such as Wi-Fi technology. The first scenario of LTE allowing LTE to operate over unlicensed bands is LTE-Unlicensed duty cycling (LTE-U). Specifically, LTE-U can coexist with Wi-Fi by allowing LTE-U devices to transmit only in predetermined duty cycles (DCs) or to use adaptive DCs for LTE based on the activity measurements. In this paper, we investigate the downlink performance of LTE-U and Wi-Fi under different traffic loads. The main novelty of this work is to exploit the knowledge of the existing Wi-Fi traffic activity to select a fixed DC for LTE. Moreover, two proposed methods to allocate the blank subframes within LTE frames are provided. Simulation results using NS-3 simulator for LTE-U and Wi-Fi coexistence mechanism under different traffic loads are provided. In particular, the results show that the coexistence mechanism between LTE-U and Wi-Fi in the 5 GHz band achieves better total aggregated throughputs for the coexisting technologies using the proposed approach. Moreover, the location of the blank subframes plays a key role in this coexistence in terms of the total aggregated throughputs.**

***Index Terms*—Almost blank subframe; Duty cycle; LTE/Wi-Fi coexistence; Unlicensed bands.**

I. Introduction

Due to the dramatic growth of data applications and services, mobile wireless networks have to greatly increase their capacities. However, the licensed spectrum is scarce leading to a challenging problem to expand the mobile networks capacities [1]. On the other hand, the unlicensed spectrum is free to use and there is about 500 MHz of free spectrum that can be utilised at the 5 GHz band. Thus, a key solution that has recently attracted researchers is to deploy mobile networks over unlicensed spectrum, enabling more efficient spectrum utilisation to provide greater capacity [2], [3].

LTE has been recently developed to operate over unlicensed bands to achieve higher throughput and better performance in dense deployments. On the other hand, unlicensed spectrum bands are mainly occupied by the Wi-Fi technology. Thus, deploying LTE over unlicensed bands can cause a performance degradation for the existing Wi-Fi technology. This led researchers to propose different approaches and techniques to allow LTE to coexist fairly with Wi-Fi over unlicensed bands.

Currently, there are two main approaches for LTE over unlicensed spectrum, LTE-Unlicensed (LTE-U) and LTE-Licensed Assisted Access (LTE-LAA) . LTE-U was developed by the industry consortium LTE-U Forum for countries such as USA and China where there is no need for Listen Before Talk (LBT) mechanism for the transmission over unlicensed spectrum [4]. On the other hand, LTE-LAA was proposed by the 3rd Generation Partnership Project (3GPP) in Release 13 for countries such as Europe and Japan where the LBT mechanism is mandatory for operation over unlicensed spectrum bands [5].

LAA uses an LBT mechanism, which is similar to the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme used by the Wi-Fi technology. Specifically, the Carrier Aggregation (CA) concept is considered to aggregate carriers from licensed and unlicensed bands [4]. A periodic check to sense the channel before transmission is mandatory. In particular, when a Base Station (BS) or a device needs a transmission, it should detect the energy level for a time equal to the Clear Channel Assessment (CCA) time period. Thus, some modifications are necessary to the LTE air interface protocol. On the other hand, in LTE-LAA, LTE BSs should send a reservation signal to prevent Wi-Fi transmissions for the next frame. Moreover, LTE BSs cannot begin the transmission until this condition is satisfied, which can degrade the total aggregated throughputs for both technologies due to this control overhead. Overall, it is worth mentioning that LTE-LAA enables a more fair coexistence than LTE-U (in terms of throughput and latency) over unlicensed bands at the expense of a significantly increased design complexity [6].

On the other hand, LTE-U does not need modifying the LTE Physical/Medium Access Control (PHY/MAC) standards since no LBT mechanism is needed. Different mechanisms are used for better coexistence of LTE-U/Wi-Fi technologies over unlicensed bands such as carrier selection, ON/OFF switching, and Carrier Sense Adaptive Transmission (CSAT) [7], which are already part of the legacy 3GPP standard and enable a straightforward deployment in existing networks. LTE-U depends on a duty-cycling technique with a light sensing scheme (i.e., CSAT) to adapt the Duty Cycle (DC) for LTE. Moreover, LTE-U employs adaptive DC based on CSAT to adapt the ON/OFF duration for LTE channel access [8]. In general, LTE-U is significantly simpler than LAA, which makes of it a more attractive candidate in scenarios where simplicity and low cost are essential, and this technology constitutes the focus of this work.

Several mechanisms for spectrum sharing between LTE-

U and Wi-Fi have been proposed in the literature. In [9], the coexistence between LTE-U and Wi-Fi networks over unlicensed bands has been studied and the results show that there is a trade-off between throughput and latency for this coexistence. In particular, the throughput has been affected by more than half by setting the DC for LTE-U to be 50%. In [4], LTE-U and Wi-Fi are deployed together using the carrier aggregation concept. The simulation results show that there is an improvement in the LTE-U throughput without any degradation of the Wi-Fi performance. The coexistence between LTE-U/Wi-Fi using CSAT and the coexistence between LTE-LAA/Wi-Fi using LBT mechanism are investigated in [10]. The results show that both scenarios can provide the same fairness for Wi-Fi transmissions if a suitable fair rate allocation is used. A model for the channel access probability in Wi-Fi while coexisting with LTE-U has been provided in [11]. The concept of Almost Blank Subframes (ABS) with a fixed DC in LTE-U has been used in [12] for LTE-U/Wi-Fi coexistence. The simulation results show that the ABS concept can improve the Wi-Fi throughput. On the other hand, Qualcomm [13] recommends that LTE-U uses a period of 40, 80 or 160 ms with a maximum DC of 50% where the LTE-U BSs have to observe the channel for dynamic channel selection and adaptive duty cycling. An analytical model for LTE-U/Wi-Fi coexistence with a fixed DC has been presented in [14]. The simulation results show that fairness can be achieved by tuning the DC parameter. Moreover, increasing the number of Wi-Fi nodes while LTE-U DC equals to 50% improves the throughput compared with an identical Wi-Fi network.

In general, for LTE-U/Wi-Fi coexistence, most previous work has focused on selecting pre-defined fixed DCs for LTE-U for particular network conditions and have provided the results for different settings for the LTE-U DC. Extensive studies analysing different coexistence mechanisms within the same framework with comparable results taking into account the traffic statistics for the existing Wi-Fi network are missing in the literature. In this paper, we focus on LTE-U with fixed duty cycling due to its design simplicity, where the DC for LTE-U is selected based on the traffic statistics of the existing Wi-Fi network. Moreover, we exploit the concept of ABS to allow the Wi-Fi transmissions at certain subframes where the highest throughput can be achieved.

Our key contributions can be summarized as follows:

1) A new approach to select a fixed DC for LTE-U in coexistence with Wi-Fi technology over 5 GHz band is proposed based on the Wi-Fi activity statistics of the ON/OFF time periods.

2) Two methods to allocate the blank subframes within the LTE-U frames are proposed based on the Wi-Fi activity statistics. In Method A, the blank subframes are selected to be at the end of the DC period, while in Method B, the blank subframes are selected to be the contiguous subframes aligned with the longest Wi-Fi transmission (i.e., longest Wi-Fi ON time) within the DC period.

The rest of the paper is outlined as follows. In Section II, the Wi-Fi and LTE-U access mechanisms are described. In Section III, a new fixed DC approach to select the LTE-U DC for a fair coexistence between LTE-U and Wi-Fi is introduced, where we implement two methods for allocating the blank subframes for better performance. In Section IV, the methodology and the simulation environment are presented. In Section V, the simulation results are presented and discussed. In Section VI, the conclusions are summarized.

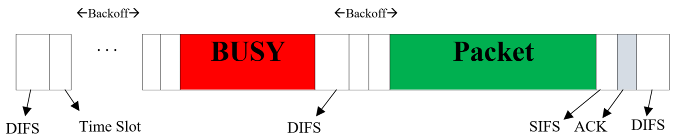

Fig. 1. Wi-Fi CSMA/CA contention scheme [15].

II. Coexistence of Wi-Fi and LTE-U: MAC Protocol Mechanisms

This section presents a brief review of Wi-Fi and LTE-U technologies to highlight their basic differences.

A. Wi-Fi Technology

In Wi-Fi technology, the Distributed Coordination Function (DCF) MAC is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism [15] as illustrated in Fig. 1. In particular, each Wi-Fi node that transmits must ensure that the medium has been idle for a DCF Interframe Space (DIFS) time. DIFS uses the carrier sensing and the Energy Detection (ED) mechanisms. If the channel has been detected to be idle for the DIFS duration, the node then transmits. Otherwise, if the channel is busy, the node persists with monitoring the channel until it is measured to be idle for a DIFS period, then it selects a random back-off time and counts down. Specifically, a node generates a random back-off timer uniformly distributed within some lower and upper bounds. Once the back-off timer decreases to zero, the node transmits a packet. For a successful transmission, the receiver will transmit an Acknowledgment frame (ACK) after a Short Interframe Space (SIFS) time.

B. LTE-U Technology

The industry consortium LTE-U Forum proposed LTE-U for the transmission over unlicensed bands for countries such as USA, Korea and China. These countries have no regulation that mandates LBT for transmission over unlicensed spectrum. Three main mechanisms have been proposed to allow coexistence between LTE and Wi-Fi over the unlicensed bands as illustrated in Fig. 2. First, LTE-U performs a channel selection to scan all the channels in the unlicensed bands. If a clear channel is detected, LTE-U will occupy this channel for Secondary Down Link (SDL) transmission with a full DC. Otherwise, if there is no clear channel, CSAT mechanism is used allowing LTE-U to share the same channel with Wi-Fi. In CSAT mechanism, LTE-U can share the same channel with Wi-Fi by using the Time Division Multiplexing (TDM) concept when the scanning procedure cannot detect a clear channel. In particular, the LTE BS senses the medium and based on the measured medium activities, CSAT can turn off LTE transmissions proportionally. Thus, LTE-U is periodically activated and deactivated by control elements. CSAT uses the DC concept to adjust the ON/OFF ratio and during CSAT ON periods, LTE-U can transmit with high power. On the

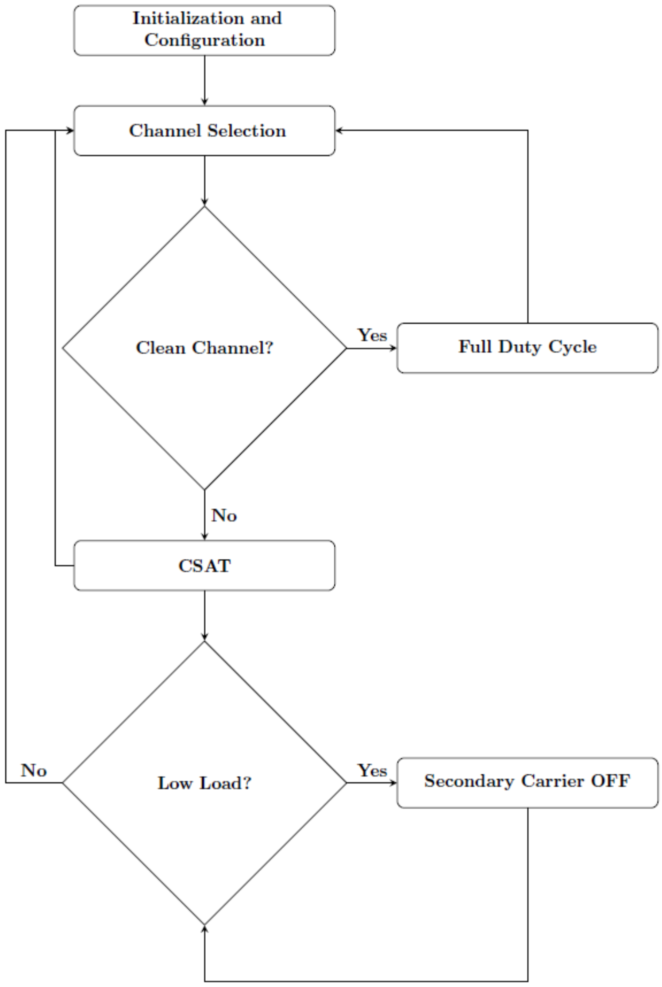

Fig. 2. Coexistence flow chart for LTE-U [4].

other hand, during CSAT OFF periods, LTE-U will be turned off to avoid interference to Wi-Fi transmissions. Specifically, the CSAT algorithm in LTE-U is implemented by using the Almost Blank Subframe (ABS) feature [16].

The third mechanism to deploy LTE with Wi-Fi over unlicensed band without LBT algorithm is the Opportunistic SDL (OSDL). The OSDL transmission is based on the load demand. In particular, if the LTE BS has a high downlink load, SDL transmissions should be turned ON, while for low downlink loads, the SDL transmission should be turned OFF to reduce the interference to the Wi-Fi transmissions and other LTE-U operators. This mechanism is suitable for dense deployments [17].

In general, deploying LTE with Wi-Fi over unlicensed bands is called LTE-U duty-cycling where transmissions are managed by the ON/OFF time periods. Moreover, it is worth mentioning that the LTE-U Forum specifications [8] provide limits for the ON/OFF durations. Specifically, the maximum ON duration is 20 ms and the minimum ON duration is 4 ms, while the minimum OFF duration is 1 ms, leading to a maximum DC of 95%. Moreover, LTE-U employs an adaptive DC mechanism based on the CSAT algorithm, i.e., it adapts and changes its DC based on the channel activity measurements.

Overall, LTE-U has key advantages such as the fact that it relies on mechanisms provided by the legacy 3GPP specifications, thus removing the need of big adaptations for the LTE specification, it is suitable where there are free channels to increase the capacity and it is not complex to be implemented. Therefore, to enhance the performance for LTE-U/Wi-Fi coexistence, a new approach with a fixed DC for LTE-U is here proposed. In addition, two methods for ABS allocation based on the Wi-Fi activity statistics are proposed in this work as well.

III. The Proposed Approach and Methods

The current LTE-U employs an adaptive DC based on the medium activity measurements (i.e., its DC is dynamic). This may degrade the total aggregated throughputs for the coexisting networks since both networks have to change their DCs proportionally. On the other hand, the ON/OFF activity statistics of the existing Wi-Fi network could be exploited to set a static DC for LTE-U. In particular, the Wi-Fi activity statistics can be estimated by the LTE-U network based on energy detection (see [18] for details). LTE-U can compute the DC for the existing Wi-Fi network after observing the channel for a sufficient long time. Then, the DC for LTE-U can be set as follows

$$DC_{LTE-U} = 1 - DC_{Wi-Fi} \tag{1}$$

Instead of updating the DC for LTE-U (i.e., DC_{LTE-U}) based on the activity statistics, DC_{LTE-U} will be kept static. The procedure is illustrated in Table I, which shows the DCs for Wi-Fi and LTE-U estimated by the LTE-U network for different traffic loads in terms of the number of packets per second (λ). This approach describes the proposed DC setting strategy for LTE-U.

Qualcomm recommends that LTE-U uses a period of 40, 80, or 160 ms [13]. In this work, we consider a 40 ms DC period, which is divided into 40 1-ms subframes. The decision of LTE-U to transmit or not in each of these subframes can be represented with a vector of 40 bits, except for subframes 0 and 35, which are reserved for the Master Information Block (MIB) and the System Information Block 1 (SIB1) respectively. This approach allows for several DC settings for LTE-U strategies. In this work, we consider the following two methods to allocate the blank subframes:

1) Method A: This method defines the location of the adequate number of blank subframes to be selected within the LTE-U frame. The number of blank subframes are selected based on the Wi-Fi activity statistics as shown in equation (1). In addition, the blank subframes are selected to be at the end of the duty cycle period as illustrated in Fig. 3a.

2) Method B: This method is similar to Method A but defines different location for the blank subframes within the LTE-U frame. In particular, the blank subframes are selected to be contiguous subframes aligned with the longest Wi-Fi transmission within the DC period. The motivation for this method is to hopefully achieve better total aggregated throughputs for the existing networks because the blank subframes are allocated alongside the longest Wi-Fi transmission time leading to less collisions between the coexisting networks. Fig. 3b illustrates the ABS implementation for this method.

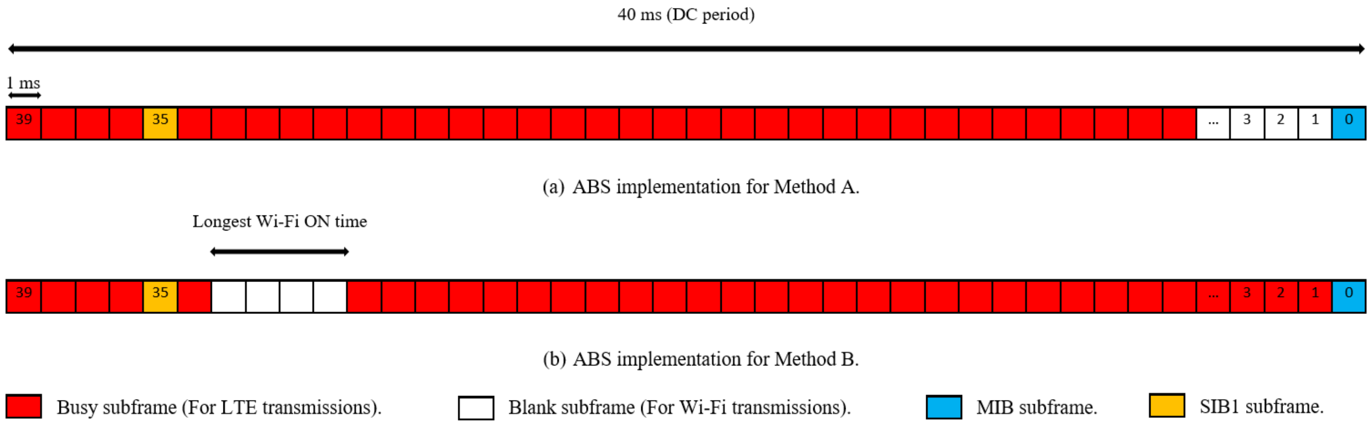

Fig. 3. The ABS pattern for the proposed methods for $\lambda = 1.0$ packets/second.

TABLE I
THE DUTY CYCLES FOR WI-FI AND LTE-U UNDER DIFFERENT TRAFFIC LOADS

λ (packets/second)	**0.5**	**1.0**	**1.5**
DC_{Wi-Fi}	0.05	0.10	0.125
DC_{LTE-U}	0.95	0.90	0.875

IV. METHODOLOGY AND SIMULATION SETUP

We evaluate the coexistence performance for LTE-U and Wi-Fi following the current LTE-U simulation conditions except the updating strategy for DC_{LTE-U}, where the proposed fixed DC for LTE-U strategy is implemented. In this paper, the performance for LTE-U and Wi-Fi networks has been evaluated using NS-3. In particular, we consider an indoor scenario with two operators; operator (A): Wi-Fi and operator (B): LTE-U using the same 20 MHz channel over the 5 GHz band. Fig. 4 describes the implementation for the LTE-U/Wi-Fi indoor scenario. Each operator deploys 4 eNodeB (eNBs)/Access Points (APs) and they are equally spaced. 20 User Equipments (UEs)/Stations (STAs) are randomly distributed for each operator. All the nodes (i.e., eNBs/APs/UEs/STAs) are equipped with two antennas for 2x2 Multiple Input Multiple Output (MIMO) scheme. In addition, the Wi-Fi nodes detect each other at -62 dBm but they detect the LTE-U nodes at -82 dBm. On the other hand, LTE-U nodes detect the Wi-Fi nodes at -72 dBm. Moreover, the employed traffic model simulates file transfers arriving according to a Poisson process with arrival rate λ . The File Transfer Protocol (FTP) has been implemented to operate over User Datagram Protocol (UDP). A file size of 0.5 MB is considered with various recommended arrival rates ($\lambda = 0.5, 1.0, 1.5$ packets/second) [19]. The simulation scenario details are provided in Table II.

In order to estimate the activity statistics for the existing Wi-Fi network, two Wi-Fi networks are deployed together. In this scenario, the DC for the existing Wi-Fi network can be estimated. The DC for LTE-U (i.e., DC_{LTE-U}) can then be evaluated and set based on equation (1). Finally, one of the Wi-Fi networks is replaced by an LTE-U network for final simulations, allowing LTE-U/Wi-Fi coexistence and assessing the validity of the proposed methods.

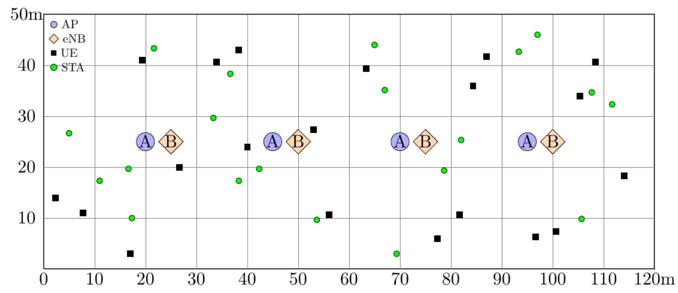

Fig. 4. Indoor layout with two operators with 4 cells per operator and 5 STAs/UEs per cell.

TABLE II
DEPLOYMENT SCENARIO AND SIMULATION PARAMETERS

Parameter	**Value or description**
Network layout	Indoor scenario
System bandwidth	20 MHz
Carrier frequency	5 GHz
Total BS Tx power	18 dBm
Total UE Tx power	18 dBm
Propagation loss model	ITU InH
Antenna pattern	2D omni-D
BS antenna gain	5 dBi
UE antenna gain	0 dBi
UE noise figure	9 dB
ABS pattern duration	$40ms$
Tx Opportunity (TxOP)	$8ms$
Slot duration	$9\mu s$
UE dropping	Randomly
Traffic model	FTP model 1

V. SIMULATION RESULTS

The performance of LTE-U and Wi-Fi networks is investigated in this section using the proposed approach to set the DC for LTE-U (i.e., DC_{LTE-U}) and using the proposed methods to allocate the blank subframes based on the Wi-Fi activity statistics. We provide the individual throughputs for Wi-Fi and LTE-U networks as well as the total aggregated throughputs for both networks. Moreover, the LTE-U latency using the proposed methods is also provided.

In Fig. 5, the throughputs for Wi-Fi, LTE-U and the total aggregated throughputs for different DC_{LTE-U} at $\lambda = 0.5$ packets/second using the proposed approach (i.e., using equation (1)) and method A are presented. It can be seen that as

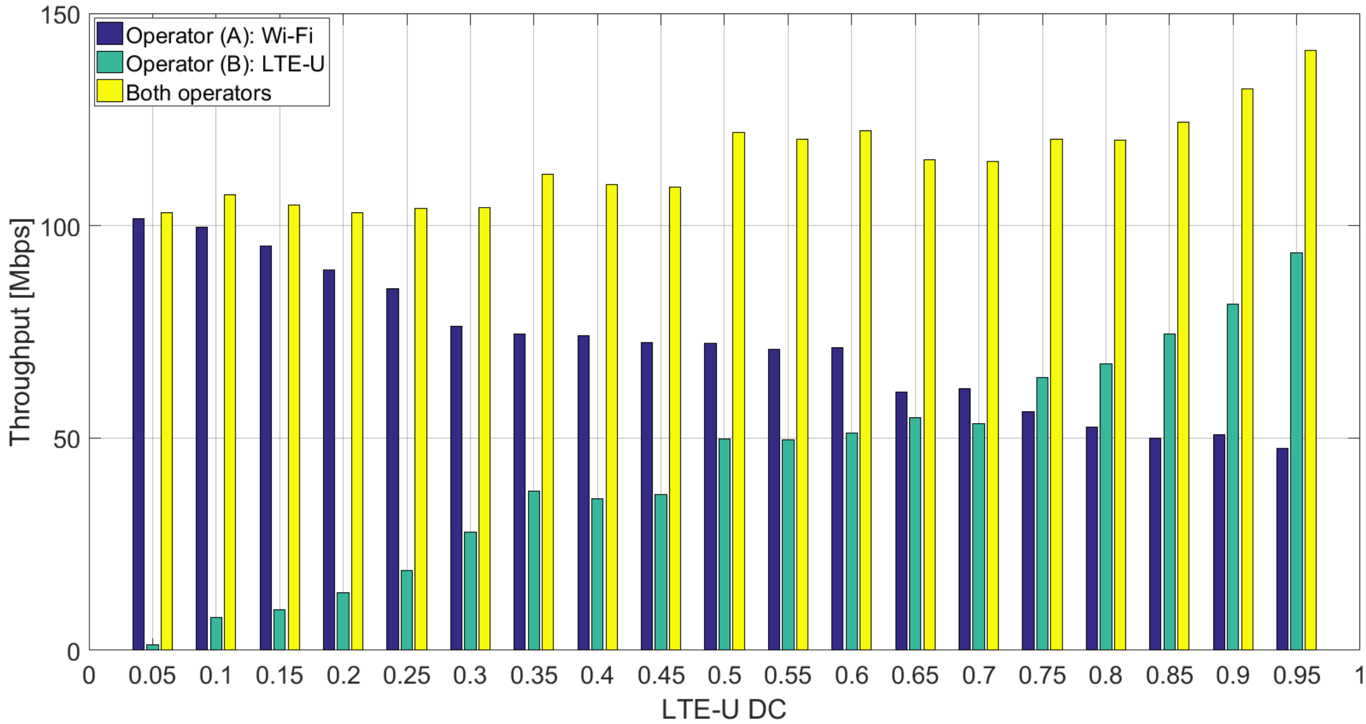

Fig. 5. Throughputs for 95% of users for both coexisting operators using different DCs for LTE-U.

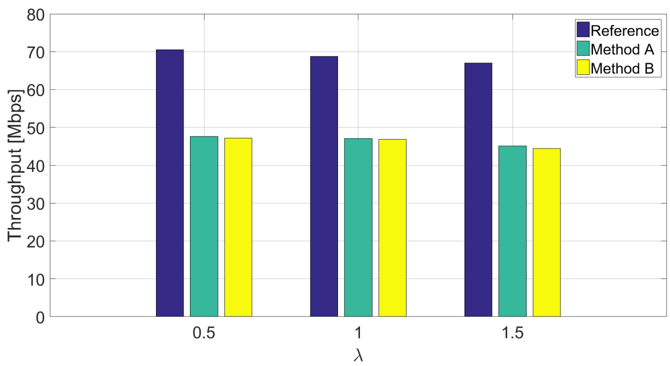

Fig. 6. Operator (A): Wi-Fi throughputs for 95% of users using different methods under different traffic loads.

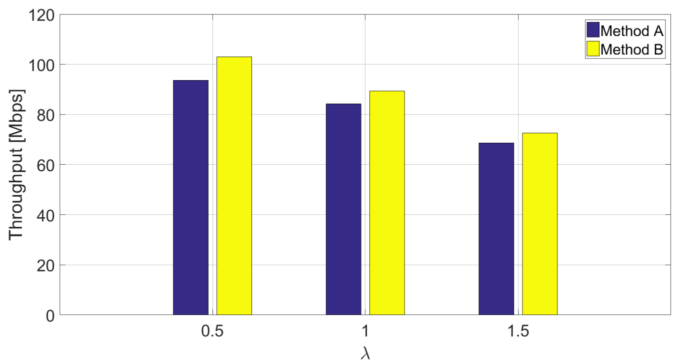

Fig. 7. Operator (B): LTE-U throughputs for 95% of users using different methods under different traffic loads.

the DC_{LTE-U} increases, the Wi-Fi throughput decreases due to allocating less blank subframes for Wi-Fi transmissions. On the other hand, the LTE-U throughput increases as the DC_{LTE-U} increases since we allow more subframes for LTE-U to transmit its own data. In general, it is observed that the maximum aggregated throughput for both networks can be achieved at $DC_{LTE-U} = 0.95$. Thus, coexisting LTE-U with Wi-Fi using DC_{LTE-U} set to be 0.95 at $\lambda = 0.5$ achieves the highest total aggregated throughput for the coexisting networks. Thus, instead of updating the DC_{LTE-U}, a fixed DC_{LTE-U} at certain value can achieve the best total aggregated throughput. In addition, the proposed approach to set the DC_{LTE-U} based on the existing Wi-Fi activity statistics provides the best total aggregated throughput compared to other static arbitrary DCs for LTE-U.

Fig. 6 presents the Wi-Fi throughputs for the existing Wi-Fi network for the reference case (i.e., Wi-Fi and Wi-Fi coexistence) and the two methods considered, under different traffic loads. It can be seen that coexisting LTE-U with Wi-Fi impacts the existing Wi-Fi throughput compared to the reference case. Moreover, it can be seen that both proposed methods achieve a comparable performance in terms of Wi-Fi throughput. The LTE-U throughputs for the two proposed methods (i.e., Method A and Method B) considered with different traffic loads are depicted in Fig. 7. In this case, it can be observed that Method B achieves better LTE-U throughput performance compared to Method A. A throughput performance improvement of 10% (9.4 Mbps), 6% (5.1 Mbps) and 5.5% (3.8 Mbps) is observed for λ = 0.5, 1.0 and 1.5 packets/second, respectively. These results indicate that a smart allocation of the blank subframes based on the Wi-Fi traffic patterns can improve the LTE-U throughput without any

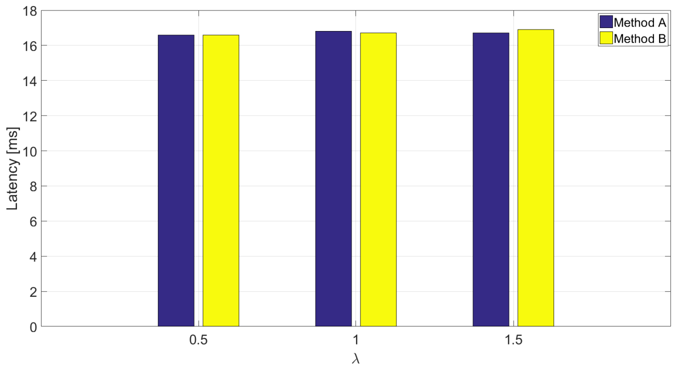

Fig. 8. Operator (B): LTE-U latencies for 95% of users using different methods under different traffic loads.

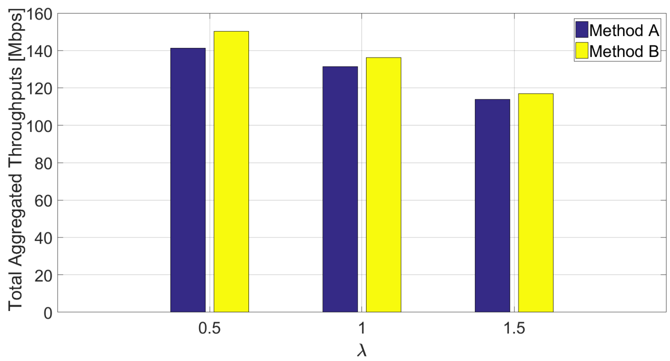

Fig. 9. Total aggregated throughputs for 95% of users for both operators using different methods under different traffic loads.

impact at all on the Wi-Fi throughput performance.

Fig. 8 reperesents the LTE-U latencies for the two proposed methods under different traffic loads. It can be noticed that both methods achieve a comparable performance in terms of latency.

Finally, the total aggregated throughputs for both networks (i.e., LTE-U and Wi-Fi) are depicted in Fig. 9. It can be seen that Method B provides better total aggregated throughputs compared with Method A. The performance improvement is 6.4% (9 Mbps), 3.7% (4.8 Mbps) and 2.7% (3.1 Mbps) for λ = 0.5, 1.0 and 1.5 packets/second, respectively. This improvement is due to the blank subframes in Method B being selected to be contiguous aligned with the longest Wi-Fi transmission within the DC period. It is worth highlighting that these performance improvements are obtained at no cost at all.

VI. Conclusion

The current LTE-U employs an adaptive DC for coexisting with Wi-Fi over unlicensed spectrum bands. This approach does not achieve the best performance in terms of total aggregated throughput of the coexisting technologies. A novel and simple approach with fixed DC for LTE-U is proposed to select the DC for LTE-U based on the knowledge of Wi-Fi traffic activities to achieve a better performance for the coexisting technologies. Moreover, two methods that define the location of the adequate number of blank subframes to be selected within the LTE-U frame are proposed. The obtained simulation results show that the proposed methods can achieve a significant improvement in the LTE-U throughput without any impact on the Wi-Fi throughput, thus enhancing the capacity available to LTE-U at no cost.

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