Duet: An Adaptive Algorithm for the Coexistence of LTE-U and WiFi in Unlicensed Spectrum

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***Abstract*—LTE in Unlicensed band (LTE-U) has gained intensive attention recently due to its capability to offload mobile data to unlicensed bands. In order to use unlicensed band, LTE-U has to coexist with WiFi - another wireless technology that operates in unlicensed bands. This coexistence is riddled with several challenges as these technologies use different core networks, backhauls and deployment plans. Within this broad paradigm, we present *Duet*, a Medium Access Control (MAC) layer solution that enables both LTE-U and WiFi nodes to operate fairly and efficiently, with the following properties: (1) no changes in WiFi framework, (2) high performance of LTE-U and WiFi networks within static and dynamic load scenarios, and (3) robustness to fully and partially connected networks. Using ns-3, we simulate *Duet* in various scenarios and show that *Duet* can improve the overall network throughput by up to 74%.**

Keywords: LTE-U, Wi-Fi, coexistence mechanism, simulation performance evaluation, ns-3

I. Introduction

The global mobile data usage is expected to grow 53% annually from 2015 to 2020 [1]. The huge mobile data usage requirement drives the mobile industry to embrace the formidable challenge and invent next-generation mobile technologies. Long-Term Evolution (LTE), as a successful mobile technology, has gained enormous importance in recent years because it brings higher data rates as well as lower latency to mobile communication systems.

Despite recent advances, LTE still may not be able to meet the mobile data challenge due to the spectrum scarcity in licensed bands. To tackle this problem, Qualcomm introduced LTE-U [2] focusing on operation in unlicensed bands, aiming at assisting cellular operators to offload cellular data to unlicensed bands. Due to the maximum power limitation in unlicensed bands, small cell is an ideal application to operate LTE-U. Small cell technology is a promising solution to offload cellular traffic as it can provide better local channel capacity compared with macro cell [3]. Thus, combining LTE-U with small cell can further relieve the traffic burden of overloaded cellular networks.

In order to operate in the unlicensed spectrum, LTE-U has to compete with other wireless technologies that operate in the same unlicensed spectrum. Among these, WiFi is widely popular with high density deployment. It is not trivial for LTE-U and WiFi to coexist as-is due to the differences in their MAC protocols. LTE-U uses a centralized MAC protocol, while WiFi uses a distributed MAC protocol. The distributed nature of MAC in WiFi makes the traffic patterns of individual clients random and unpredictable. Also, LTE-U and WiFi transmissions can interfere with each other. Therefore, it is hard for LTE-U to coexist with WiFi without communication guidelines at system level that ensure fair access to the spectrum for both of these technologies while maintaining high efficiency of the channel.

The context of this paper is the coexistence between a wireless network with centralized MAC (e.g. LTE-U) and a wireless network with distributed MAC (e.g. WiFi). There are several solutions proposed in related literature to solve the coexistence problem. However, they either require extra time resources for sensing the channel, thereby leading to less channel efficiency [9]-[11] or they do not consider fairness metrics, different load conditions and hidden terminal problems [2]. In this context, we present *Duet*- an algorithm that triggers the coexistence between LTE-U and WiFi networks, while ensuring fair resource allocation and high channel efficiency in both LTE-U and WiFi networks.

Specifically, the main contributions of this paper are: 1) We propose *Duet*, an algorithm to adaptively tackle the coexistence problem of LTE-U and WiFi through an enhanced ON/OFF duty cycle mechanism, in which LTE-U transmissions are allowed during the LTE-U ON period and WiFi transmissions are allowed during the LTE-U OFF period. *Duet* can be applied to both fully and partially connected networks with either static or dynamic network load; 2) we evaluate *Duet* through ns-3 simulations in various scenarios and show that it can improve the overall network throughput up to 74% while maintaining good channel utilization and fairness between LTE-U and WiFi networks.

The rest of this paper is organized as follows: Section II provides the background and motivation on the coexistence of LTE-U and WiFi. Section III formally defines the coexistence problem and the scope. Section IV outlines the *Duet* algorithm. Section V evaluates *Duet* using ns-3 simulations. Finally, Section VI describes the related work and Section VII concludes the paper.

II. A primer on LTE-U/WiFi coexistence

LTE-U uses a centralized MAC protocol, where the small cell base station schedules time and frequency resources among all User Equipment (UE). By assigning resources using a scheduling algorithm such as a proportional fair scheduler,

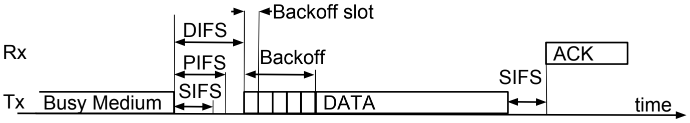


Fig. 1: DCF Mechanism

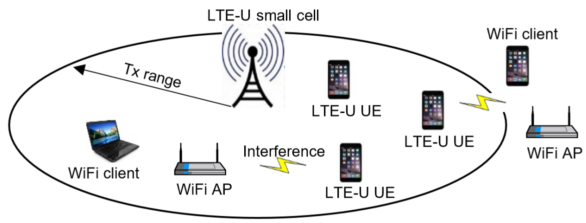


Fig. 2: LTE-U - WiFi coexistence

the small cell ensures maximum channel efficiency without starvation of UEs.

The most popular WiFi MAC, Distributed Coordination Function (DCF), is a contention based distributed MAC protocol. Fig. 1 shows the mechanism of DCF. DCF is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), in which a WiFi station only transmits when the channel is sensed idle. More specifically, DCF includes a backoff mechanism in the WiFi station that generates a random backoff number from [0,cw], where cw is the contention window size. The backoff counter decreases as long as the channel is sensed idle after a time period DIFS. When the backoff counter reaches zero, it triggers the corresponding WiFi station to transmit a packet. Upon successful reception of the packet, the receiver transmits an ACK back to the sender after a time period SIFS. However, it is possible that more than one station chooses the same backoff number. In this case, stations transmit at the same time and lead to a collision. If collision happens, cw will be doubled and the process repeated from channel sensing.

If LTE-U and WiFi networks operate in the same spectrum as-is, throughput of the WiFi network will be significantly reduced. (as shown in Section V). This is because the LTE-U controller, in an effort to maximize the channel efficiency of the LTE-U network, always allows the small cell and UEs to transmit, keeping the channel busy and thus the WiFi stations cannot transmit. Even in the case when a WiFi node transmits, there is a chance of collision with LTE-U packets, since LTE-U small cell and UEs do not listen to the channel before transmitting. Therefore, if WiFi and LTE-U nodes were to operate in the same spectrum, a good coexistence algorithm is required to achieve high channel efficiency and fair resource allocation of LTE-U and WiFi nodes.

III. Problem Definition and Scope

In this section, we formally define the LTE-U and WiFi coexistence problem.

A. Problem definition

Consider the scenario shown in Fig. 2, with one LTE-U small cell, N_{lteu} UEs and N_{wifi} wifi nodes. For the LTE-U network, all LTE-U UEs are connected to the LTE-U small cell. For the WiFi network, all WiFi nodes can hear each other. The connectivity between each LTE-U UE i and WiFi node j is represented by connectivity matrix M:

$$M = \begin{bmatrix} x_{11} & x_{12} & x_{13} & \dots & x_{1n} \\ x_{21} & x_{22} & x_{23} & \dots & x_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & x_{m3} & \dots & x_{mn} \end{bmatrix}$$

where $x_{i,j}$ is defined as below:

$$x_{ij} = \begin{cases} 1 & \text{if LTE-U UE } i \text{ can hear WiFi node } j \\ 0 & \text{if LTE-U UE } i \text{ can't hear WiFi node } j \end{cases}$$

Given the matrix M, the goal is to find a solution to the coexistence problem that results in high overall network throughput while maintaining fairness between LTE-U and WiFi networks. Without a condition on fairness, LTE-U and WiFi networks can selfishly grab more resources for its own transmission, and harm the overall network throughput.

In this paper, we evaluate fairness through a proportional fair defined at link-level granularity. We choose proportional fair metric over other fairness metrics, because it allocates the same amount of time resources to each active WiFi and LTE-U link[1]. Note that, the solution in this paper can be easily extended to other fairness metrics discussed in [4]. Also, as allocating time resources is technology agnostic, proportional fairness criterion is assumed to be reasonable in most scenarios. Proportional fairness between LTE-U and WiFi is reached when the $Lteu_{proportional}$ (average airtime of LTE-U network) is equal to $Wifi_{proportional}$ (average airtime of WiFi network):

$$Wifi_{proportional} = Lteu_{proportional} \tag{1}$$

The airtime of a WiFi link is defined by the sum of successful transmission time, contention time (e.g. DIFS, SIFS and backoff time), collision time and transmission delay. The airtime of a LTE-U link is defined by the sum of transmission time and transmission delay. The average airtime of WiFi a network is defined as:

$$Wifi_{proportional} = \frac{C_{wifi}}{L_{wifi}} \tag{2}$$

The average airtime of a LTE-U network is defined as:

$$Lteu_{proportional} = \frac{C_{lteu}}{L_{lteu}} \tag{3}$$

where, L_{lteu} and L_{wifi} are the number of links in the LTE-U and WiFi networks, respectively. C_{lteu} and C_{wifi} represent the time usage of LTE-U and WiFi networks, respectively.

To summarize, the goal of this paper is to propose an algorithm that allocates time resources to WiFi and LTE-U networks to maximize overall network throughput while achieving the fairness condition in Equation 1.

[1]Note that uplink and downlink can be assigned with different weighted factor for specific scenario.

B. Scope

The scope of this paper is limited to the following constraints: 1) Each LTE-U UE is equipped with a WiFi interface and it is always turned on[2]; 2) Unlicensed spectrum is used as LTE-U supplemental downlink capacity; 3) There is no hidden terminal problem in the WiFi network[3].

IV. Duet: Adaptive Coexistence Algorithm for LTE-U and WiFi

In this section, we describe the *Duet* algorithm. *Duet* achieves coexistence through an ON/OFF duty cycle mechanism. We first consider a fully connected network where all WiFi nodes can be heard by all LTE-U nodes. In this scenario, we propose Duet-*baseline* where the LTE-U ON/OFF period is linearly or proportionally adapted based on the channel utilization of LTE-U and WiFi networks. We later relax the connectivity constraints and consider a partially connected network. We propose Duet-*SCU (Slotted Channel Utilization)* in partially connected scenarios, where channel utilization is estimated based on slotted time block, and LTE-U ON/OFF period is linearly or proportionally adapted based on the slotted channel utilization of LTE-U and WiFi networks.

A. Baseline Algorithm

We first consider a fully connected network topology ($x_{i,j}$ equals to 1 for all i and j) and introduce the *Duet-Baseline* algorithm. *Duet-Baseline* involves the following two parts: 1) Channel utilization estimation, and 2) Duty cycle adaptation.

1) Channel Utilization Estimation: Accurate channel utilization estimation is the core to the *Duet-Baseline* algorithm. In this section, we describe how channel utilization is estimated in both LTE-U and WiFi networks. Since LTE-U uses a centralized MAC protocol, LTE-U transmission time can be easily estimated by the LTE-U small cell. More specifically, LTE-U network information (L_{lteu} and $D_{lteu,i}$, where $D_{lteu,i}$ denotes the airtime of LTE-U packet i) is gathered in LTE-U small cell. WiFi channel utilization is measured by the WiFi interface of LTE-U UE. More specifically, the WiFi interface of LTE-U UE gathers WiFi network information ($D_{wifi,i}$ and L_{wifi}, where $D_{wifi,i}$ denotes the airtime of WiFi packet i), and LTE-U UE reports corresponding information to LTE-U small cell. Let T_e represent the estimated time usage of WiFi transmission, and Bk_e represent the estimated backoff number, which is calculated through a Markov chain based model for contention window size [14]. In order to calculate Bk_e, each WiFi interface of the LTE-U UE overhears and maintains a list of active MAC addresses of WiFi links and updates it periodically. Let D_{packet} and D_{ack} represent the packet duration of the packet and the ACK, respectively. These terms can be accessed by decoding the preamble or through Clear Channel Assessment (CCA) measurement. In Algorithm 1, T_e is estimated by the WiFi interface of LTE-U UE in three different conditions: 1) receiving a data packet in line 3[4]; 2) receiving an ACK in line 5; 3) packet collisions in line 7. The details for estimating channel utilization time can be referred to Algorithm 1.

Algorithm 1 WiFi Channel Utilization Time Estimation

1: $T_e = 0$
2: **if** Receive a data packet **then**
3: $\quad T_e += DIFS + Bk_e + D_{packet} + D_{prop}$
4: **else if** Receive an ACK **then**
5: $\quad T_e += SIFS + D_{ack} + D_{prop}$
6: **else if** Collision happens **then**
7: $\quad T_e +=$ Channel utilization time of largest packet
8: **end if**

Channel utilization is defined by T_e divided by LTE-U OFF period for each duty cycle. The estimated WiFi channel utilization is in the range of [0,1], and it is piggybacked on the LTE-U packet and reported to LTE-U small cell at the start of LTE-U ON period.

2) Duty Cycle Adaptation: The LTE-U ON/OFF period is linearly or proportionally adapted based on the channel utilization of LTE-U and WiFi in *Duet*. LTE-U small cell allocates time resources to LTE-U and WiFi networks by defining LTE-U ON and OFF period. The small cell sends packets to the UEs through LTE-U links only in LTE-U ON period. Simultaneously, the small cell will track the actual transmission time of LTE-U traffic in LTE-U ON period. WiFi transmissions are allowed during the LTE-U OFF period. To prevent WiFi transmissions during the LTE-U ON period, we can let the WiFi interface of LTE-U UE broadcast CTS-to-self during the LTE-U ON period with a specific Network Allocation Vector (NAV). The WiFi interface of LTE-U UE estimates the time usage of WiFi traffic in LTE-U OFF period. The sum of a LTE-U ON and OFF period is defined as a duty cycle. Based on the time usage of LTE-U and WiFi links and the corresponding LTE-U ON/OFF period, the LTE-U small cell can calculate the channel utilization of LTE-U and WiFi networks. The LTE-U small cell can assign an ON/OFF period to both LTE-U and WiFi traffic of the next duty cycle according to the channel utilization of the current cycle.

The coexistence algorithm of *Duet-Baseline* consists of two phases - linear adaptation and proportional adaptation. In the proportional/linear adaptation phase, the LTE-U ON/OFF period are proportionally/linearly adapted towards maximizing channel utilization/fairness based on the measured channel utilization of LTE-U and WiFi. We illustrate these phases through an example. Consider a scenario where in L_{lteu} is equal to L_{wifi}. Let $Wifi_{cu}$ (channel utilization of WiFi in the previous duty cycle) and $Lteu_{cu}$ (channel utilization of LTE-U in the previous duty cycle) be 50% and 100%, respectively. Also, assume C_{wifi} and C_{lteu} to be 100*ms* and 80*ms*, respectively. If the LTE-U ON/OFF period is proportionally adapted, C_{wifi} and C_{lteu} will be set to 50*ms* (100*50%)

[2]Most of devices with LTE-U interface have WiFi interface, e.g. cell phone.

[3]The priority of this work is to investigate hidden terminal between LTE-U and WiFi. Also, hidden terminal problem between WiFi nodes has been widely investigated in related literature [7]-[8].

[4]We ignore the propagation delay (D_{prop}), as it is negligible compared to other delays due to the limited transmission range of a small cell.

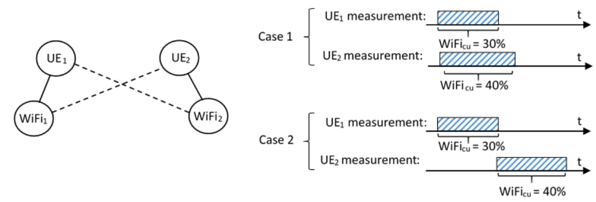


Fig. 3: Example scenario, where solid line and dotted line represent overhear is possible and impossible

and 130*ms* (80+100*50%), respectively, for the current duty cycle. Then, maximum channel utilization can be achieved using *Duet*. On the other hand, if the duty cycle length is linearly adapted, C_{wifi} and C_{lteu} will be 99*ms* (100-1) and 81*ms* (80+1), respectively, in the current duty cycle. Then, the LTE-U ON/OFF period is adapted towards achieving the fairness between LTE-U and WiFi.

We define *Thres* as channel utilization threshold to trigger linear or proportional adaptation mechanism. The range of *Thres* is [0,1]. As shown in Algorithm 2, if $Wifi_{cu}$ and $Lteu_{cu}$ are both lower or higher than *Thres*, linear adaptation is utilized to let C_{wifi} and C_{lteu} converge to the proportional fairness in line 6 and 8. Otherwise, proportional adaptation is utilized, and C_{wifi} and C_{lteu} can be proportionally adapted to maximize channel utilization in line 2 and 4. If *Thres* is set closer to 1, proportional adaptation is triggered more frequently and the LTE-U ON/OFF period are adapted more aggressively. Linear Adaptation and Proportional Adaptation (LAPA) algorithm of *Duet* can be referred to Algorithm 2.

Algorithm 2 Linear Adaptation and Proportional Adaptation

1: **if** $Wifi_{cu} >= Thres$ **and** $Lteu_{cu} < Thres$ **then**
2: Proportionally adapt C_{lteu} and C_{wifi}
3: **else if** $Wifi_{cu} < Thres$ **and** $Lteu_{cu} >= Thres$ **then**
4: Proportionally adapt C_{lteu} and C_{wifi}
5: **else if** $Wifi_{cu} >= Thres$ **and** $Lteu_{cu} >= Thres$ **then**
6: Linearly adapt C_{lteu} and C_{wifi} towards fairness
7: **else if** $Wifi_{cu} < Thres$ **and** $Lteu_{cu} < Thres$ **then**
8: Linearly adapt C_{lteu} and C_{wifi} towards fairness
9: **end if**

B. Partially connected scenario

In this section, we expand the constraints of *Duet-Baseline* and consider a partially connected scenario (viz. scenario with hidden terminal between LTE-U and WiFi networks), where the elements of the connectivity matrix M are not always 1. For this scenario, we propose *Duet-SCU*.

In *Duet-baseline*, the LTE-U UE reports the WiFi channel utilization to LTE-U small cell. However, in a partially connected network, this information is not enough for the LTE-U small cell to decide the LTE-U ON/OFF period for next cycle. This is because, each LTE-U UE has a different view of the network and hence has different WiFi channel utilization information. Consider the example scenario shown in Fig. 3 where two UEs can hear different WiFi nodes (connectivity between UE and WiFi forms matrix M). Let UE_1 and UE_2 estimate the channel utilization individually to be 30% and 40% of LTE-U OFF period, respectively. Cases 1 and 2 represent WiFi transmissions in different time periods. The actual channel utilization for case 1 and 2 is 40% and 70%, respectively, and is different from the estimations made by the UEs. Thus, the channel utilization estimates from a single UE is not enough to compute the overall channel utilization. To have an accurate picture, the timing information of the transmissions is also needed.

TABLE I: ns-3 Parameters

Parameters	Default Settings
Frame size	1500bytes
Adaptation threshold	90%
Initial LTE-U ON/OFF period	90/90ms
Minimal LTE-U ON/OFF period	10ms
Duty cycle period	180ms
Propagation loss model	Friis propagation loss model
Wi-Fi Tx power	23dbm
Wi-Fi basic transmission rate	6Mbps
Wi-Fi data transmission rate	54Mbps
Wi-Fi CCA Threshold	-62dBm
Wi-Fi CS/CCA Threshold	-82dBm
LTE-U small cell Tx power	23dbm
LTE-U transmission rate	dynamic rate control

Reporting time information of each WiFi packet (start and end time of each WiFi packet transmission) to the LTE-U small cell can be a solution. However, it requires tight time synchronization and generates significant reporting overhead. To alleviate this problem, we introduce slotted channel utilization measurement method. We define each slot as a time block. The WiFi interface of each LTE-U UE measures the channel utilization during each slot with duration D_{slot} according to Algorithm 1. Following that, the $Wifi_{scu}$ for each slot is set as follows:

$$Wifi_{scu} = \begin{cases} 1 & \text{if } Wifi_{cu} > \text{ half of } D_{slot} \\ 0 & \text{if } Wifi_{cu} <= \text{ half of } D_{slot} \end{cases}$$

$Wifi_{scu}$ is reported to the LTE-U small cell periodically by piggybacking this information with the Channel State Information (CSI) reports[5]. The LTE-U ON/OFF period in *Duet-SCU* are adapted according to the LAPA algorithm as shown in Algorithm 2. Using this algorithm can alleviate tight time synchronization, since reporting time slot utilization requires rougher time synchronization compared with reporting time information of each WiFi packet. Also, reporting time slot utilization lead to less reporting overhead compared with reporting time information of each WiFi packet.

V. EVALUATION

In this section, we evaluate the *Duet* under static/dynamic traffic loads, partial/fully connected topologies using normal/slotted channel utilization estimation. We use system throughput and channel utilization to evaluate the LTE-U and WiFi network performance. We evaluate fairness using LTE-U ON/OFF period. If LTE-U ON/OFF period achieves the

[5]CSI reports are periodically sent to the small cell by default

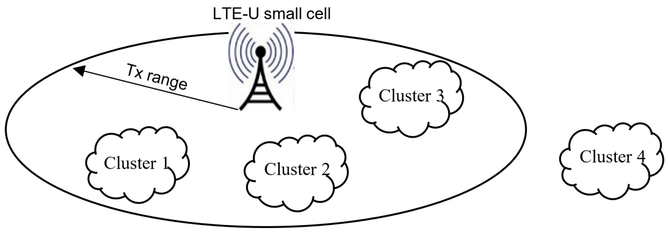


Fig. 4: Partially connected scenario

condition shown in Equation 1, then proportional fairness is achieved.

A. Methodology

We evaluate *Duet* using simulations in ns-3 [15]. Various parameters of the WiFi and LTE-U network are shown in Table I. The simulation parameters for WiFi and LTE-U follow the 802.11a[6] [16] and FCC requirements [17], respectively. To eliminate any random biases, we repeat each experiment 10 times with different random seeds.

The two different topologies considered in the simulations are explained below:

- *Fully connected topology:* The fully connected topology consists of a LTE-U small cell with 8 UEs uniformly distributed around it in a circle of radius 50m. Also, in this circle, 4 WiFi APs, each with a station attached to it, are uniformly distributed. In this scenario, every LTE-U UE can overhear all WiFi transmissions.
- *Partially connected topology:* To generate a partially connected topology, we set up 2 node clusters for LTE-U UEs (Cluster 1 and Cluster 2) with each cluster containing 4 UEs. We also set 2 node clusters for WiFi (Cluster 3 and Cluster 4). Cluster 3 and Cluster 4 contain k ($k \in [0, 3]$) and $4 - k$ pairs of WiFi AP and client. The default value of k is 3. Nodes in Cluster 1 and Cluster 4 are placed such that they can't overhear each other, and Cluster 4 can't detect LTE-U small cell transmission. All the other clusters can overhear each other. Fig. 4 shows the corresponding topology. We also set the D_{slot} to be $100\mu s$, as this value achieves accurate channel utilization without requiring tight time synchronization. We also evaluate the channel utilization accuracy for different D_{slot} values later in this section.

For each of the simulation topology, we send UDP traffic to the LTE-U UEs from a remote host connected to the EPC network of the LTE-U small cell. We also generate UDP traffic between each pair of WiFi AP and client (in both uplink and downlink). The default packet arrival interval ($Interval_p$) for the traffic is 6ms. We evaluate *Duet* by injecting both static load (where the load doesn't change over time) and dynamic load (where the load changes over time). We generate dynamic load conditions by changing the $Interval_p$ at around every second (every 6th duty cycle period) as shown in Fig. 5 [7].

[6]Currently, LTE-U is designed to operate in the 5GHz band

[7]For simplicity, we use deterministic traffic model to observe whether *Duet* will adapt to different load conditions as expected

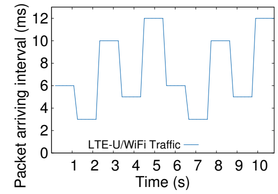
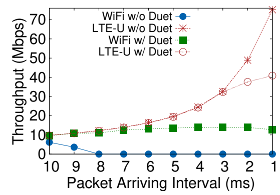
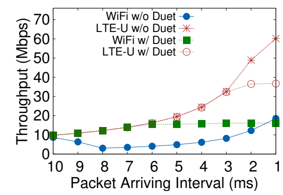


Fig. 5: Dynamic traffic pattern



(a) Fully connected topology



(b) Partially connected topology

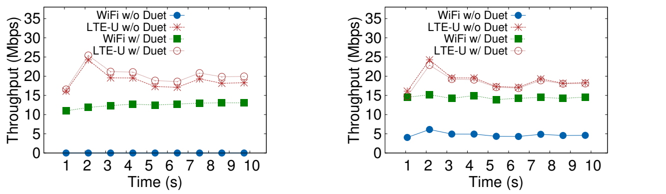
Fig. 6: Impact of $Interval_p$ on network throughput

B. Macroscopic Results

1) Effect of packet arriving interval: Fig. 6a and 6b illustrate how packet arriving interval $Interval_p$ impacts the LTE-U and WiFi network throughput in fully and partially connected topologies. Since LTE-U network shares time resource with WiFi networks after enabling *Duet*, LTE-U network throughput is nearly not impacted or decreased. In the fully connected topology, the throughput of WiFi network is significantly improved (WiFi throughput increases from 0 to 13Mbps after enabling *Duet* for packet arriving interval between 1 to 8ms). In the partially connected topology, enabling *Duet* increases the throughput by 112% for WiFi network.

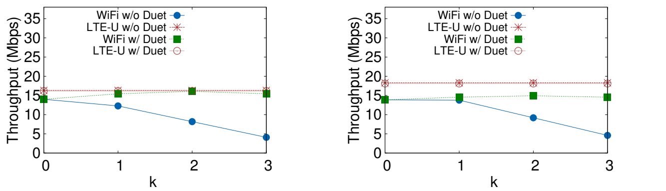
As shown in Fig. 6a, enabling *Duet* does not improve the WiFi/LTE-U throughput when packet arriving interval is large. The reason is that as traffic load is low ($Interval_p$ is large), LTE-U and WiFi can almost always find the channel to be idle for transmission without any assistance from *Duet*. As packet arriving interval becomes smaller than 8ms, WiFi throughput is nearly 0 when *Duet* is not enabled. This is because LTE-U small cell always transmits and WiFi always detects the channel to be busy. Enabling *Duet* allows the WiFi nodes to transmit without LTE-U interference during LTE-U OFF period. This increases the WiFi throughput significantly. Also, the LTE-U throughput is not impacted by *Duet* for $Interval_p$ between 3ms and 10ms. This is because the traffic is not saturated. As the size of packet from upper layers is smaller than the Transport Block Size (TBS) in the LTE-U network, the packet will be padded with 0 until it reaches the TBS. When $Interval_p$ is 1ms, the overall network throughput decreases when *Duet* is enabled. This is because LTE-U has higher transmission rate than WiFi (in our simulations), and LTE-U always transmits without letting WiFi transmit when *Duet* is disabled. However, this situation causes starvation in WiFi.

Similar trends discussed above can be observed in Fig. 6b. For the partially connected topology, the WiFi throughput is slightly higher than that of fully connected topology. This is because, there will be 1 pair of WiFi nodes in Cluster 4



(a) Fully connected topology (b) Partially connected topology

Fig. 7: Impact of load condition on network throughput



(a) Static load (b) Dynamic load

Fig. 8: Impact of k on network throughput

who are not affected by LTE-U small cell transmissions. As *Duet* is disabled, it is interesting to note that WiFi throughput decreases initially and increases afterwards. As the packet $Interval_p$ is larger than 8ms, LTE-U will transmit the amount of packets which leads to WiFi nodes in Cluster 3 waiting for an idle channel to transmit. Thus, only partial load of WiFi nodes in Cluster 3 can be transmitted, and it leads to the decrease of WiFi throughput. Since LTE-U does not impact WiFi nodes in Cluster 4, only WiFi nodes in cluster 4 transmit packets as packet arriving interval decreases from 8ms. High traffic load for WiFi nodes in Cluster 4 allows the WiFi throughput to increase.

2) Effect of dynamic load conditions: For the dynamic load conditions described in Fig. 5, Fig. 7a and 7b illustrate how LTE-U and WiFi throughput varies with time in fully connected and partially connected topologies, respectively. Enabling *Duet* improves the WiFi throughput from 0 to 13Mbps in fully connected topology and by 208% in partially connected topology.

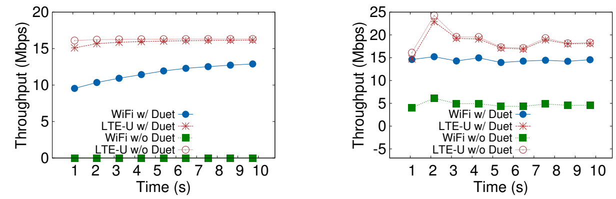
3) Effect of topology in partially connected scenario: Fig. 8a and 8b illustrate how the value of k (the WiFi AP and client pair in Cluster 3 described earlier in Section V-A) will impact on LTE-U/WiFi network throughput in static and dynamic load scenario, respectively. Enabling *Duet* improves the network throughput by 110% and 78% for WiFi network in static and dynamic load conditions, respectively. For both load conditions, as k increases, WiFi throughput without *Duet* decreases. This is because more WiFi nodes are put in Cluster 3 (recall that WiFi nodes in Cluster 3 can't transmit when LTE-U transmits).

4) Channel utilization estimation accuracy: The effect of D_{slot} on channel utilization estimation accuracy is shown in Table II. When D_{slot} decreases, the accuracy increases. This is because the reporting mechanism is error prone for larger values of D_{slot}.

We also evaluated the error of channel utilization estimation under different load conditions and at different time instances.

TABLE II: D_{slot} effect

D_{slot} (us)	50	100	150	200	250
Channel utilization accuracy	97%	97%	88%	84%	83%



(a) Case 1 (b) Case 2

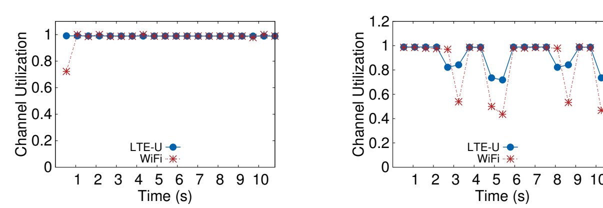
Fig. 9: Network throughput

We found the error is at most 3% for both fully connected and partially connected topologies. In the interest of brevity, we omit these results in this paper.

C. Microscopic Results

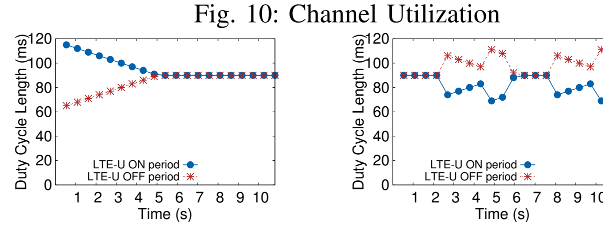
In this section we present two specific cases to show how *Duet* solves the coexistence problem in the time perspective. The goal of these studies is to illustrate that *Duet* not only achieves high network throughput, but also utilizes the channel effectively (channel utilization = 1) and is fair (LTE-U ON period = LTE-U OFF period (applied to the case when LTE-U and WiFi have the same number of links)). For each of these cases, we randomly pick one of the 10 sets of simulations and illustrate how throughput, channel utilization and LTE-U ON/OFF period change with time.

1) Case 1: Fully connected topology with static load: Fig. 9a, 10a and 11a show the system throughput, channel utilization and LTE-U ON/OFF period versus time, respectively, for both LTE-U and WiFi networks. *Duet* results in effective channel utilization, as evidenced by the channel utilization converging to 1 for both WiFi and LTE-U. However, at the beginning, the channel utilization of WiFi is low. This is due to Address Resolution Protocol (ARP) by the WiFi network before the transmission of any UDP packets. We can



(a) Case 1 (b) Case 2

Fig. 10: Channel Utilization



(a) Case 1 (b) Case 2

Fig. 11: LTE-U ON/OFF period

also observe that the duty cycle of LTE-U and WiFi adapts according to channel utilization. Overall, LTE-U and WiFi networks achieve high channel utilization (channel utilization = 1) and good fairness (LTE-U ON period = LTE-U OFF period) with *Duet* in the fully connected topology with static loads.

2) Case 2: Dynamic load and partially connected topology: Fig. 9b shows the overall network throughput of both LTE-U and WiFi networks at different time instances for the dynamic load described in Fig. 5 and with a partially connected topology (k=3). Fig. 10b and Fig. 11b show the channel utilization and LTE-U ON/OFF period, respectively, for WiFi and LTE-U networks. We can observe that the channel utilization converges to 1 in dynamic load scenario. The channel utilization of LTE-U and WiFi decreases after 2.16s when the traffic load decreases. We can observe that LTE-U utilization decreases faster than WiFi, since WiFi keeps transmitting packets left in the WiFi packet queue (LTE-U has higher transmission rate). Then LTE-U ON period is proportionally decreased and LTE-U OFF period is proportionally increased. After that, LTE-U ON period is linearly increased and LTE-U OFF period is linearly decreased towards fairness. Note that LTE-U channel utilization is higher than WiFi when traffic load is low. This is because LTE-U will pad 0 to packets with size less than TBS. Overall, LTE-U and WiFi networks achieve high channel utilization and good fairness with *Duet* in the partially connected topology with dynamic loads.

VI. Related Work

Coexistence of LTE-U and WiFi has been studied in the recent years. Through experimental analysis, [5]-[6] show that LTE has significant impact on WiFi performance in different scenarios. MAC layer coexistence mechanisms between LTE-U and WiFi are proposed in [9]-[13]. [9]-[11] introduce coexistence algorithm by implementing contention based algorithm in LAA, e.g. Listen-Before-Talk (LBT). However, LBT introduces extra delay due to the contention time overhead, which can lead to inefficient channel usage. [12] proposes a channel selection mechanisms in LTE-U to avoid channel sharing of LTE-U and WiFi. However, if a clean channel is absent, LTE-U has to hold until the channel becomes idle. [2] proposes CSAT, which is based on ON/OFF duty cycle coexistence mechanism, but no fairness model is considered, and different load condition and hidden terminal problems are out of scope of CSAT.

Offloading cellular data to WiFi networks is another method to relieve the burden of cellular networks. Systems to offload mobile traffic to WiFi network have been introduced in [18]-[19]. However, offloading cellular data to WiFi networks can generate extra overhead for system level communications, due to the different core networks and backhauls between LTE-U and WiFi.

VII. Conclusions

In this paper we present a solution for the WiFi/LTE-U coexistence problem - *Duet*. Under different traffic load and connectivity scenarios, we show that *Duet* utilizes the channel efficiently and converges to proportional fairness between LTE-U and WiFi networks. However, there are some constraints for *Duet* to work properly: (1) Each LTE-U UE needs to be equipped with a WiFi interface and it is required to be turned ON, which generates extra energy cost; (2) coexistence between LTE-U and WiFi networks is studied with LTE-U downlink only; (3) channel utilization information is only used in the very last duty period to predict current duty cycle length, which may not be accurate; (4) Hidden terminal problem for WiFi nodes is not considered. We intend to relax these constraints as a part of future work.

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