Co-existence of LTE-U and Wi-Fi with Direct Communication

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***Abstract*—One of the most prominent cellular technologies, Long Term Evolution (LTE), is currently operating on some 800MHz, 2GHz, and 3.5GHz licensed bands. Wi-Fi is currently operating on 2.5GHz and 5GHz unlicensed bands. The declaration stating that 5GHz bands are unlicensed enables LTE to operate on 5GHz bands. It is challenging, however, for different wireless technologies to co-exist. The two standards, LTE-U and LTE-LAA, for LTE to coexist with Wi-Fi on the 5GHz band have evolved. The LTE-U standard is based on the duty cycle, while LTE-LAA is based on listen-before-talk (LBT). In existing LTE-U systems, the LTE base station (eNB) estimates the fair portion of Wi-Fi usage based on channel state information. The usage estimation from channel state information is not as accurate enough as well as the fair portion. In this paper, we study the fair coexistence between LTE-U and Wi-Fi in the scenario where an LTE eNB can exchange information with Wi-Fi access points (AP). The communication can be done in both wired and wireless mediums. The wired medium is ethernet point-to-point communication, and the wireless communication is done using the reserved bits in Wi-Fi packets. Both ways are applicable to the operator, who has both LTE and Wi-Fi coverage. Therefore, the Wi-Fi AP can collect information about other APs and send it to its LTE eNB. The LTE eNB can adjust its parameters according to the received information to achieve fairness.**

Index Terms*—LTE, LTE-U, LTE and Wi-Fi coexistence, fair spectrum sharing, direct communication between Wi-Fi and LTE

I. INTRODUCTION

Wi-Fi and LTE are the most prominent wireless access technologies nowadays. LTE is efficient, and every transmission bit is utilized perfectly for efficiency. LTE is designed for operating in a licensed band and is not tolerant of interference caused by other transmissions. Therefore, LTE cannot operate perfectly in an unlicensed spectrum where heterogeneous wireless protocols exist. On the other hand, Wi-Fi is designed to be interference tolerant to operate in unlicensed bands.

The increasing number of mobile devices results in an exponential increase of data usage in wireless technology. The 84.5 MHz of unlicensed spectrum in the 2.4 GHz band, which is allocated for unlicensed usage, has been saturated for Wi-Fi [1]. There is up to 750MHz of unlicensed spectrum in the 5GHz band that falls under the Unlicensed National Information Infrastructure (U-NII) rules of the Federal Communications Commission (FCC). Currently, some Wi-Fi standards including IEEE 802.11ac, IEEE 802.11a, and IEEE 802.11n are operating in the 5GHz band. Some LTE stakeholders, including Qualcomm (an American multinational telecommunications equipment manufacturer), are also interested in the 5GHz bands. After the FCC issued a Notice of Proposed Rule Making (NPRM) 13-22 in 2013 [2], 195 MHz of spectrum was added for unlicensed usage. The Wi-Fi Innovation Act [3] directs the FCC to conduct tests to assess the feasibility of opening the upper 5 GHz band for unlicensed usage.

Enabling fair coexistence between LTE and Wi-Fi is challenging. The LTE UE or eNB does not sense a channel before transmission. They assume that the channel they are using is licensed and not occupied by other. The Wi-Fi devices sense the channel before transmission, and if the channel is occupied, it does not transmit. Therefore, LTE shows eminent behavior while coexisting with Wi-Fi. Therefore, the challenge is to ensure a fair share between LTE and Wi-Fi. There are several studies on ensuring a fair share and coexistence between LTE and Wi-Fi. Currently, there are two standards for LTE operating in the 5GHz band: duty cycle based LTE-U and LBT based LTE-LAA. Some large organizations, including Verizon, Alcatel-Lucent, Ericsson, Qualcomm, and Samsung, founded a forum to create and collaborate on standards for eNBs and user equipments (UEs). In 2014, Qualcomm research proposed Carrier-Sensing Adaptive Transmission (CSAT). The CSAT senses for a longer time in order to determine the others' channel usage information. Based on the usage, the LTE eNB decides the duty cycle. This technique is effective where the other users' usage do not change frequently. Practically, Wi-Fi usage changes frequently over time. The accurate information about other users' usage cannot be found by sensing channels. Therefore, the duty cycle needs to be adjusted based on the actual usage information of the Wi-Fi.

The problem can be solved by using direct communication to share usage information between Wi-Fi APs and LTE eNBs. The problem is that other operators might not allow their APs/eNB to be connected with other operators' APs/eNBs. In this paper, we propose a direct-communication-based coexistence mechanism. The model will be applicable to operators who have both LTE and Wi-Fi coverage, such as Comcast and Verizon. We investigate the performance of our proposed model in terms of fairness and throughput metrics under different environments.

The remainder of the paper is as follows: Section II describes some related works. Section III contains LTE and Wi-Fi channel access mechanisms and challenging issues for their consistence. Section IV describes our proposed network model. In Section V, we present our NS3 simulation results and the performance evaluation of our proposed model.

978-1-5386-8088-9/19/$31.00 ©2019 IEEE

II. Related Work

There are two standards of LTE for coexisting with Wi-Fi in an unlicensed band: carrier sensing adaptive transmission (CSAT)-based LTE-U and LBT based LTE-LAA. There are many works on the coexistence of LTE-U/LTE-LAA and Wi-Fi.

In [4], the authors present a distributed inter-frame spacing based LTE-LAA. A Defer period after the LTE back-off period and a freeze period after the clear channel assessment (CCA) are added to reduce collisions. The LBT mechanism based, fairness-aware LTE-LAA and Wi-Fi coexisting scheme is proposed in [5]. The authors present TXOP (transmitted in a single transmission opportunity) backoff for LTE-LAA eNB. The TXOP backoff is similar to the Wi-Fi exponential backup, but has different parameter values. In [6], the authors propose a Q-learning based adaptive duty cycled LTE. In [7], the authors propose an LBT enhancement algorithm that adapts contention window size for LTE with LTE-LAA in order to achieve QoS and channel access fairness.

In [8], the authors present an LTE-U based coexistence mechanism ULTRON without any modification to the LTE PHY standard. The ULTRON operates on LTE eNB and embeds Wi-Fi signals prior to the LTE sub-frames to make Wi-Fi users aware of the LTE transmission. In [9], the authors propose a dynamic spectrum coordination framework that is enabled by a software defined network (SDN) architecture. The architecture does not require any changes to existing standards. In [10], the authors propose a coexistence scheme called CU-LTE. The CU-LTE enables spectrum efficiency and fair spectrum sharing between LTE and Wi-Fi networks. The proposed scheme uses the dynamic channel selection, channel aggregation, and fractional spectrum access for LTE-U. The authors formulate an integer nonlinear optimization problem to optimize the throughput and design an algorithm. In [11], the authors do several experiments with the refined version of Wi-Fi and LTE-U. They introduce the notion of random walk in Wi-Fi performance and show that the LTE-U's negative impact on Wi-Fi performance is compensated with the refined Wi-Fi model. A blank sub-frame based coexistence model is proposed in [12] where some of the LTE subframes are muted to give chances to Wi-Fi transmissions. A Q-learning based duty cycle adjust mechanism is proposed in [13].

All of these related works assume that LTE and Wi-Fi users are competitive and will share no information directly with each other. Nowadays, there are mobile operators who have both LTE and Wi-Fi coverage. Therefore, these operators can consider the direct communication between LTE eNB and Wi-Fi AP for fair coexistence and higher throughput.

III. Technical Background

In this section, we discuss the heterogeneous architecture of LTE and Wi-Fi.

A. Wi-Fi Architecture

In this subsection, we discuss the architecture of the latest standards of Wi-Fi (IEEE 802.11) family IEEE 802.11ac. IEEE 802.11ac operates on the 5GHz band and achieves a high throughput. The throughput of IEEE 802.11ac is higher because of channel bonding, frame aggregation, and MIMO. The channel bonding is a process of aggregating multiple consecutive 20MHz channels to form 40, 80, or 160 MHz channels. Among the bonded channels, one of the 20MHz channels is used for transmitting control signals and referred to as the primary channel. The frame aggregation is a process of combining multiple frames and transmitting in a single shot. This process reduces overhead for accessing channel in the MAC layer. The frame aggregation is introduced in 802.11n and 802.11ac inherits the feature. The MIMO uses multiple antennas to increase reliability and spatial diversity of transmission [14].

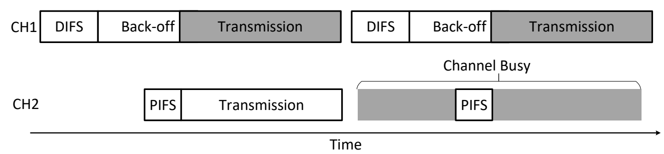


Fig. 1. IEEE 802.11ac channel access mechanism.

Now we discuss the channel access mechanism of 802.11ac. A transmitter first senses the primary channel for the distributed inter frame spacing (DIFS) time. If the channel is sensed to be free, then a random back-off counter is initialized from its current contention window (CW). During the random back-off period, if the channel is sensed to be busy, the counter freezes and continues sensing the channel. The counter resumes if the channel is free. The counter decreases by 1 in every timeslot. The transmitter transmits when the counter reaches 0. The secondary channels are sensed for a static point inter frame spacing (PIFS) period just before the counter reaches 0. If the channels are free, then they are aggregated with the primary channel. Fig. 1 shows the channel access mechanism of 802.11ac. The $CH1$ and $CH2$ are considered as the primary and secondary channels, respectively. At the beginning, the $CH1$ is sensed for the DIFS period, and the channel is free. Then a random back-off period is taken. Sensing $CH2$ starts at PIFS earlier than the end of the back-off period. The $CH2$ is sensed to be free, and the transmitter transmits in both $CH1$ and $CH2$. For the second transmission, the $CH2$ is sensed to be busy during the PIFS period. Therefore, transmission only occurs in $CH1$.

There is a lower limit and an upper limit for the CW. If the transmission is successful, then the CW is reset to the lower limit. If the transmission is not successful, then the CW is doubled or set to the upper limit, which is the minimum [15].

B. LTE Architecture

The architecture of LTE is different from Wi-Fi. LTE is designed to operate in a licensed band. Therefore, there is no sensing operation in LTE. Unlike the Wi-Fi, the channel access mechanism of LTE eNB is different than LTE UE.

The LTE uplink and downlink can be in the same band or different bands. When uplink and downlink are in separate bands, it is known as frequency division duplexing (FDD).

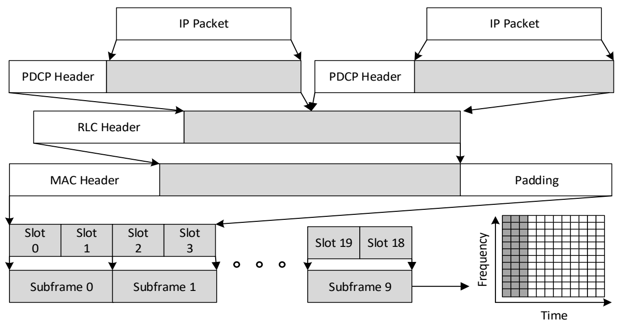


Fig. 2. LTE packet flow through different layers.

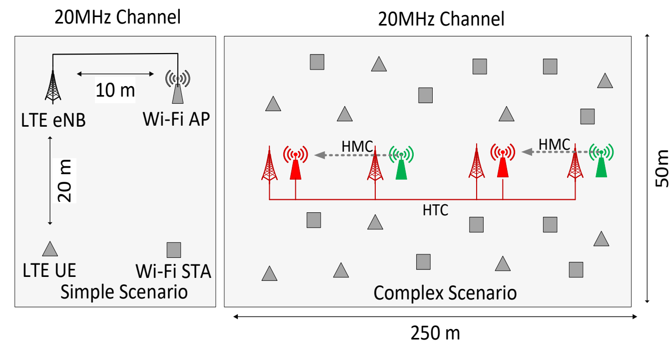


Fig. 3. Simple and Complex LTE-U and Wi-Fi coexistence.

Currently, 1-32 LTE bands are using FDD for uplinks and downlinks. When LTE uses the same band for the uplink and downlink, it uses time division duplexing (TDD). Currently, 33-48 LTE bands use TDD for uplink and downlink [16].

The LTE occupies the given band completely regardless of the uplink and downlink separation mechanism. Now, we discuss the channel access mechanism of LTE. Fig. 2 shows the packet flow through different layers. The band allocated for LTE is divided into some physical channels. The medium access control (MAC) layer maps the logical channels to some transport channels. The transport channels are finally mapped to the physical channels. The data packets (IP packets) pass through the packet data convergence protocol (PDCP), radio link control (RLC), medium access control (MAC), and physical layer (PHY). The final output is the subframes. Each subframe is 1ms long and one frame contains 10 subframes. Therefore, a frame is 10ms long. Each subframe is again divided into resource blocks by the time and the frequency domain. Then, each resource block is assigned to a UE. Multiple resource blocks can be assigned to a UE. The first few blocks (gray colored resource blocks in Fig. 2) contain block assignment information. Therefore, these blocks are important, because if the blocks get lost, then the whole subframe is meaningless.

C. LTE and Wi-Fi Coexistence Challenges

We observe that Wi-Fi throughput is 0 when LTE and Wi-Fi operate in a 20MHz channel of the 5GHz band(in Fig. 5(a) when the LTE duty cycle is 1). The experiments conducted by Nokia Research [17] show that in coexistence scenarios, the Wi-Fi network is heavily influenced by LTE-U interference. Specifically, the Wi-Fi APs remain on LISTEN mode more than 96% of the time, which causes severe degradation to their overall throughput.

The main reason is that Wi-Fi is CSMA/CA based and uses LBT where LTE does not use LBT. Therefore, before transmissions, an LTE eNB/UE does not consider others' transmission in the spectrum. On the other hand, a Wi-Fi user senses the channel for DIFS period before transmission, finds that the channel is busy, and keeps silent if LTE transmission is going on. Generally, a Wi-Fi transmission does not start during an LTE transmission, but an LTE transmission can start during a Wi-Fi transmission. As a result, collision occurs and both packets get lost. The automatic repeat request mechanism of LTE retransmits the collided packet and the CW of Wi-Fi is doubled. Therefore, Wi-Fi waits for a longer time to retransmit the lost packet.

LTE-U is one of the solutions for LTE and Wi-Fi coexistence. It uses the duty cycling method to keep quiet periodically to give Wi-Fi a chance. The duty cycle is determined by the LTE eNB based Wi-Fi usage. The Wi-Fi usage information is found by sensing the channel for a longer period of time. Choosing the appropriate duty cycle is challenging in this way, because the usage of Wi-Fi AP/STA changes frequently and the exact usage information cannot be found by sensing the channel. Therefore, direct communication between Wi-Fi AP and LTE eNB is necessary. The problem is that an operator will not allow their AP/eNB to be connected with other operators' AP/eNb. Therefore, the direct communication is limited to mobile operators who provide both LTE and Wi-Fi networks.

IV. System Model

In this section, we describe our proposed network model, LTE-U direct communication, and define metrics for evaluating fairness in network coexistence.

A. Network Model

Our network consists of two operators: A and B. Operator A has coverage for both LTE and Wi-Fi. Operator B has only Wi-Fi coverage. There can be only two types of communication. The first type of communication is between provider A's LTE eNB and provider A's Wi-Fi AP. Let's denote this communication as heterogeneous communication (HTC). The second type of communication is between provider A's Wi-Fi AP and provider B's Wi-Fi AP. Lets denote this communication as homogeneous communication (HMC). These two types of communications can be performed in several ways. HTC is possible when the eNB has capability of a Wi-Fi module, or the Wi-Fi AP has a LTE module. It is also possible if the eNB and AP have wired connection, like Ethernet. The HMC does not require any extra module. It is not possible to have a wired connection between different operators Wi-Fi AP. Therefore, wireless communication is the only way. The wireless communication can be done using reserved bits of the Wi-Fi packets. Fig. 4 shows the packet format of 802.11ac and 802.11n. In the OFDM PHY VHT modulation of 802.11ac, the VHT-SIGA field contains VHTSIG-A1 and VHT-SIG-A2 fields. The VHT-SIG-A1 has two separate reserved bits. In

Algorithm 1 Duty cycle adjustment

Input: Deviation Δ, current duty cycle d_{old}, Wi-Fi throughput T_w, and LTE throughput T_l.
Output: New duty cycle.

```
Procedure: ADJUST-DUTY-CYCLE(Δ, d_old, T_w, T_l)
    if Δ > Th then
        if T_w > T_l then
            d = d_old × α.
        else
            d = d_old / α.
    else
        if T_w > T_l then
            d = d_old + β.
        else
            d = d_old − β.
    return d.
```

addition, the VHT-SIG-A2 has a reserved bit, and the VHT Signal B field has 2 to 3 reserved bits. Hence, we have at least 5 reserved bits that are used to embed Wi-Fi information. In the OFDM PHY of 802.11n, there is one reserved bit in the HT-SIG field which is not enough for sharing usage information. The signal field in DATA is 16 bits long and the first 7 bits are used to synchronize the descrambler, while the rest of the 9 bits are reserved. This reserved bit can be used to embed the Wi-Fi information. The HTC/HMC can be used for sending various information from Wi-Fi AP, including current throughput, air time, and collision rate. In this article, we consider that the operator A uses the LTE-U mechanism to operate in one of the 20 MHz unlicensed channels on the 5GHz band. The operator A has wired communication between its Wi-Fi AP and eNB. A's Wi-Fi AP collects Wi-Fi usage information (if possible) and shares the information, including its own usage information with the eNBs. For simplicity, we consider only the throughput as usage. The eNBs adjust their duty cycle based on the throughput of Wi-Fi AP.

B. LTE and Wi-Fi Coexistence Using Direct Communication

The HMC has limited space to carry information. The five (or nine) bits can represent 32 (or 512) levels of throughput in 802.11ac (or 802.11n). The maximum theoretical throughput of Wi-Fi depends on the protocol and the modulation type. For example, if 16-QAM and 1/2 coding rate is used, the maximum data rate is 86.7Mbps with a 400ns guard interval in a 20MHz channel of 5GHz band. If 64-QAM and 2/3 coding rate is used, the maximum data rate is 173.3Mbps with a 400ns guard interval. Therefore, we consider a 5Mbps interval for levels. For example, throughput between [0,5), [5,10), and [10,15) Mbps will be level 0, 1, and 2. Level 31 will be [155, $+\infty$) for 802.11ac. Similarly, for 802.11n, we can consider a 0.33 Mbps interval for levels.

The Wi-Fi AP of operator A keeps track of the throughput of operator B. Whenever A's Wi-Fi AP receives a packet containing the throughput information, it updates the entry for that AP. Therefore, A's Wi-Fi AP maintains a list which contains up-to-date $< PhysicalAddress, Throughput >$ pair of all nearby Wi-Fi APs. The Wi-Fi AP periodically sends this list to eNB. The eNB decides its duty cycle based on the throughput information. The aim is to ensure fairness among the LTE UEs and Wi-Fi STAs. Therefore, in a high traffic

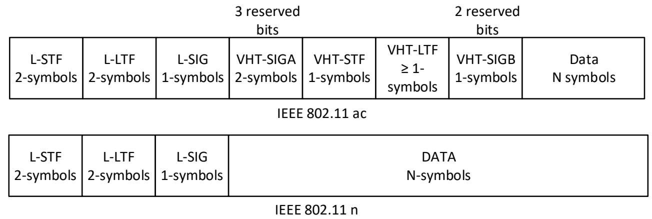


Fig. 4. 802.11ac and 802.11n packet format.

scenario, if the throughput of LTE is higher (lower) than Wi-Fi, it reduces (increases) the duty cycle.

To define a fair portion of the spectrum, we do an experiment with an LTE eNB, a Wi-Fi AP, an LTE user, and a Wi-Fi user. We change the duty cycle of LTE from [0,1] and observe the throughput of both LTE and Wi-Fi. The throughput and the duty cycle are plotted in Fig. 5(a) and Fig. 5(b) for simple and complex scenarios. After observing the figures, we notice three points: (1) The duty cycle where the total throughput is highest, (2) The duty cycle where LTE throughput and Wi-Fi throughput are similar, and (3) The 0.5 duty cycle. Therefore, an ideal coexistence scenario ensures the total throughput is maximized, while also guaranteeing equal throughput and equal spectrum usage time for participant network technologies. Meeting these three criteria is difficult because of the heterogeneous architectures of the spectrum access technologies.

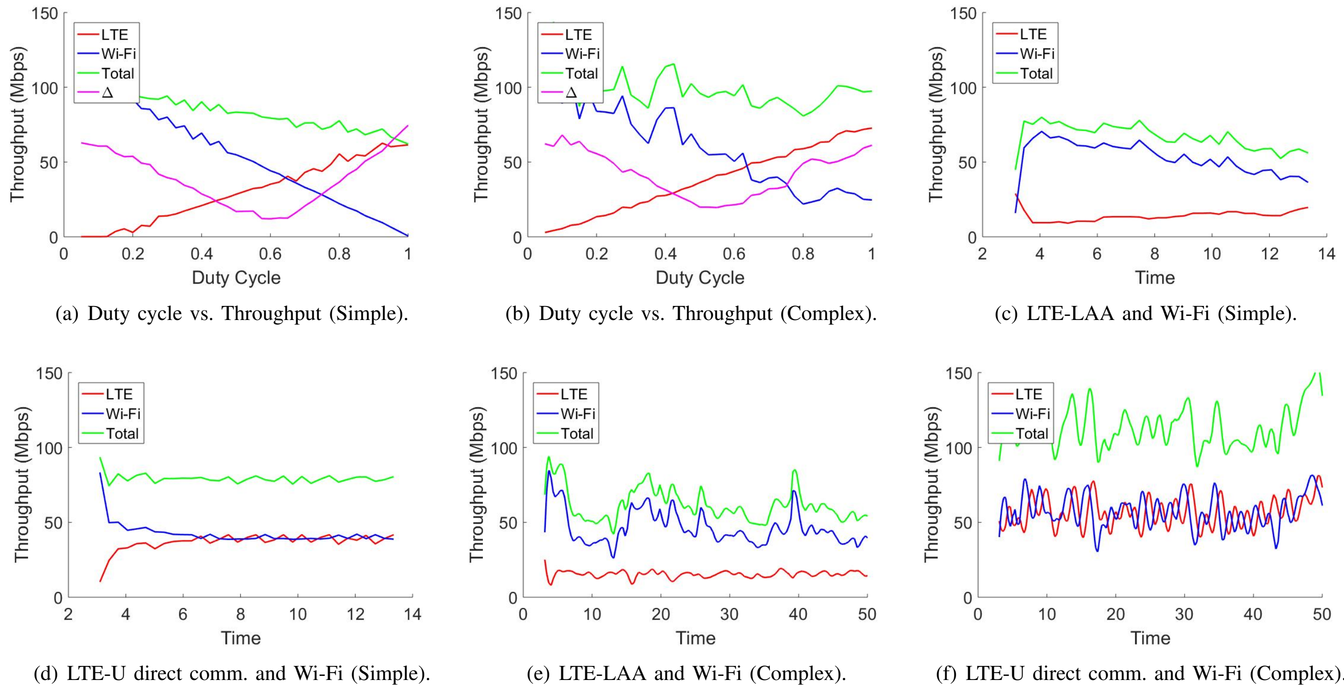
We denote the deviation from the ideal coexistence scenario by Δ. The Δ will be the summation of three measurements: deviation from the maximum throughput (δ_T), deviation from equal spectrum occupancy time (δ_t), and deviation from equal throughput (δ_s).

$$\Delta = \frac{1}{3}(\delta_t + \delta_T + \delta_s), \quad \delta_t = 2 \times |0.5 - d|,$$
$$\delta_T = \frac{T_{max} - T_{avg}}{T_{max}}, \quad \delta_s = \frac{1}{N}\sum_{n=1}^{N} \frac{|T_n - T_{avg}|}{T_{avg}} \tag{1}$$

Here, d is the duty cycle of LTE/Wi-Fi. T_{max} and T_{avg} are the maximum and average combined throughputs. T_n is the throughput of user n, and N is the total number of competitor technologies (N=2 for LTE and Wi-Fi). In our scheme, the adjustment of d happens in two ways: progressive and linear. In the progressive adjustment, d is increased (or decreased) by a factor, and in the linear adjustment, d is increased (or decreased) by a constant. If the previous duty cycle is d_{old} and it is reduced by a factor α (or a constant β), then according to the progressive (or linear) adjustment, the new duty cycle d_p (or d_l) is:

$$d_p = \alpha \times d_{old}, \quad d_l = \beta + d_{old} \tag{2}$$

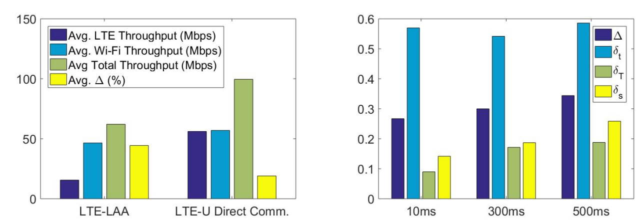
When the value of Δ is high (or low), we need to adjust the d significantly (or smoothly). Therefore, we define a threshold Th. If the value of Δ is higher than Th, then we adjust d according to the progressive rule; otherwise, we adjust d according to the linear rule. The duty cycle adjustment process is shown in Algorithm 1.



(a) Duty cycle vs. Throughput (Simple). (b) Duty cycle vs. Throughput (Complex). (c) LTE-LAA and Wi-Fi (Simple).

(d) LTE-U direct comm. and Wi-Fi (Simple). (e) LTE-LAA and Wi-Fi (Complex). (f) LTE-U direct comm. and Wi-Fi (Complex).

Fig. 5. Simulation results LTE-U and Wi-Fi coexistence.



(a) Overall comparison between LTE-U Direct comm. and LTE-LAA. (b) Delay and fairness in LTE-U Direct comm.

Fig. 6. More simulation results.

V. Experimental Details and Simulation

A. Experimental Settings

We conduct NS3 simulations on two scenarios: the simple scenario and the complex scenario.

a) The Simple Scenario: In this scenario, we have an LTE eNB, a Wi-Fi AP, an LTE UE, and a Wi-Fi STA. The eNB and AP are positioned 10m away from each other. The UE and STA are positioned 20m away from the eNB and AP respectively. The eNB and AP have an Ethernet HTC. When a packet is transmitted successfully (receives acknowledgement from the receiver) from the AP, it updates its throughput and broadcasts the throughput information over the Ethernet. A UDP broadcast packet is constructed, containing the physical address and throughput. The broadcast happens once every 300ms. Fig. 3 (left) depicts the simple scenario.

b) The Complex Scenario: In this scenario, we have four LTE eNBs, four Wi-Fi APs, ten LTE UEs, and ten Wi-Fi STAs. Operators A and B deploy small cells in a $50m \times 120m$ indoor space. Operator A deploys four LTE eNBs and two Wi-Fi APs. The operator deploys the remaining two Wi-Fi APs, and the eNBs are positioned at coordinates $(20, 25)$, $(45, 25)$, $(70, 25)$, and $(95, 25)$. The APs are positioned 5m after each eNB. The eNBs and APs of operator A are connected to each other by the Ethernet. The APs of operator B embed their throughput information with the Wi-Fi packet header to share with operator A's APs. The throughput information is updated in the same way as the simple scenario. Unlike the simple scenario, a UDP broadcast packet is constructed by operator A's APs, containing the list of physical addresses and the throughput. The broadcast happens once in every 300ms. Fig. 3 (right) depicts the complex scenario.

We consider channel 36, which has a frequency of 5170MHz-5190MHz (20MHz) in the 5GHz band. There is no channel bonding in the Wi-Fi because it is operating in a channel. We consider the IEEE 802.11n for Wi-Fi and LTE-U Duty Cycle model. For comparison, we consider the LAA model in LTE Release 13. The transmission power of all devices is set to 18dBm with a gain of 5. The NS3 indoor loss model is used as the propagation model. We conduct simulations for 15s to 50s and observe the throughput of LTE, Wi-Fi, Δ by varying the duty cycle according to our proposed model. The source UE/STA continuously creates UDP packets of 1024 bytes and sends them to another UE/STA. Therefore, the channel remains highly saturated during the simulation period.

B. Simulation Results

At first, we conduct a simulation for 50 seconds by varying the duty cycle $[0, 1]$ in both simple and complex scenarios. We find similar behavior in the throughput and Δ. We observe that the duty cycle within $[0.5, 0.65]$ provides low Δ. Therefore, in a high traffic scenario, the duty cycle should be kept within $[0.5, 0.65]$ to ensure fair coexistence. Figs. 5(a) and 5(b) depict the LTE, Wi-Fi, total throughput, and Δ by duty cycle for both simple and complex scenarios.

We compare the performances of the LBT based LAA model with our proposed model. Fig. 5(c) depicts the simulation results. We observe that there is a huge gap in the throughput between LTE-LAA and Wi-Fi. The Wi-Fi dominates over LTE-LAA. The average throughput of LTE and Wi-Fi are respectively 14.18 Mbps and 52.74 Mbps. It is hard to get the actual channel occupancy time of both LTE-LAA and Wi-Fi. Therefore, consider that the channel access time is proportional to its throughput ($\delta_t = \delta_s$). We keep $\alpha = 1.1$, $\beta = 0.02$, and $Th = 0.40$. The average Δ is 43.21%. On the other hand, the proposed model shows a good performance in terms of fairness and throughput. Fig. 5(c) shows the performance of the proposed LTE model and Wi-Fi. The LTE starts with a low duty cycle and adjusts the duty cycle based on Wi-Fi throughput. After some time, the LTE and Wi-Fi throughput gradually become similar. The average LTE and Wi-Fi throughputs are 36.74 Mbps and 42.59 Mbps, while the average Δ is 14.82%, which is much better than LTE-LAA and Wi-Fi coexistence.

Fig. 5(e) shows the coexistence of LTE-LAA and Wi-Fi in a complex scenario. The performance is similar to the simple scenario. The average throughputs of LTE and Wi-Fi are 15.56 Mbps and 46.57 Mbps, respectively. The average δ is 54.51%. On the other hand, the average throughput of LTE and Wi-Fi is 56.18 Mbps and the average throughput in the proposed LTE model with Wi-Fi coexistence is 57.00 Mbps. The average δ is 19.02%. Fig. 5(f) depicts the performances of the proposed LTE and Wi-Fi coexistence system. If we look closely at the throughputs of LTE and Wi-Fi in Fig. 5(f), we find that the Wi-Fi throughput peaks are followed by the LTE throughput peaks. This is caused by the transmission delay from the Wi-Fi AP to the LTE eNB. When an LTE eNB starts decreasing the duty cycle, the effect is applied immediately on Wi-Fi APs and STAs. Because of the delay in transmissions and the interval of throughput broadcasts, the eNB gets the Wi-Fi throughput later. That is why we observe a smaller delay in the Wi-Fi throughput peak (low/high) than the LTE throughput peak (high/low). We conduct a simulation to observe the effects of delay in usage packet transmission. Fig. 6(b) shows the δ_t, δ_T, δ_s, and Δ by delay of usage packet transmission. We can observe that when delay is high the deviation from the ideal scenario is high.

Fig. 6(b) shows the comparison between the LAA-LTE and LTE direct communication models. In summary, the throughputs of LTE and Wi-Fi are more similar to each other in our proposed model than in the LTE-LAA mode. The total throughput is higher in the LTE direct communication model. The deviation from the ideal scenario is higher in LTE-LAA than in the LTE direct communication model.

VI. Conclusion

Opening up the 5GHz band for unlicensed usage would give more room for cellular technology like LTE. This also brings challenges to achieve fairness of usage and good utilization. In this paper, we propose a model for achieving fairness between LTE and Wi-Fi. The model is based on direct communications between the Wi-Fi AP and LTE eNB. The Wi-Fi AP shares its usage information to eNB, and eNB dynamically adjusts its duty cycle based on the Wi-Fi usage information. An operator does not allow their network devices to be connected to other operators' devices. Therefore, our proposed model is limited to the area where the operator has both LTE and Wi-Fi network coverage. Though the system is limited to a small scenario it can achieve better fairness and throughput than LTE-LAA.

Acknowledgments

This research was supported in part by NSF grants CNS 1757533, CNS1629746, CNS 1564128, CNS 1449860, CNS 1461932, CNS1460971, and IIP 1439672.

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