Coexistence of LTE-U and WiFi in 5GHz: Challenges and Solutions

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***Abstract*—The growing demand for wireless communication necessitates efficient spectrum sharing between heterogeneous technologies like LTE-Unlicensed (LTE-U) and WiFi, both operating in the 5GHz band. This paper explores the mechanisms, challenges, and solutions for the coexistence of LTE-U and WiFi, aiming to achieve fair and efficient spectrum utilization. I delve into the intricacies of LTE-U, highlighting carrier aggregation and its implications for unlicensed spectrum usage. I address the challenges of ensuring fairness and high efficiency in coexistence scenarios through novel solutions such as Hyper Access Points (HAP) and association fairness techniques. Additionally, I propose embedding LTE-U within WiFi bands to enhance coexistence without altering existing WiFi protocols. The paper introduces LtFi, a cross-technology communication system enabling direct interaction between LTE-U and WiFi, facilitating interference management and spectrum optimization. My findings emphasize the importance of innovative coordination strategies and cross-technology communication to improve overall network performance and coexistence in the 5GHz spectrum**

***Index Terms*—WiFi, Virtualization capable WiFi, NFV, LAA, LTE-U, CTC, LtFi**

I. INTRODUCTION

Wireless local area networks are used by devices to access the Internet and communicate with each other in small areas. Devices connect to a router or access point(AP) through the IEEE 802.11 protocol without the help of a wired medium.

Technologies like cellular networks, the Internet of Things(IoT), and machine-to-machine communication (M2M) are causing an increase in Wireless traffic because more and more devices are being connected using the technologies mentioned above. In the last decade, there has been more internet traffic, which WiFi networks have transported than their wired counterparts. It is expected that WiFi devices will take over 56.8 percent of internet traffic by 2022 [5]. With an ever-increasing number of WiFi end-users, it is necessary that the existing WiFi technologies should be optimized. On the other hand, WiFi technology itself has also evolved over the years. According to Cisco's white paper, the average WiFi network connection speed was 24.4 Mbps in 2017, and it will exceed 54.2 Mbps by 2022 [5]. Besides the IEEE 802.11 standard protocol, a new version of the WiFi standard has also been introduced, 802.11ax, which is designed to operate in all band spectrums between 1 and 7GHz, including the existing 2.4GHz and 5GHz. In order to avoid interference among the neighboring devices and to improve the efficient utilization of the spectrum, the operation band spectrum certainly will move from 2.4GHz to 5GHz or even higher band.

At the moment, these technologies, in general, and WiFi in particular, are not able to effectively use these spectrum resources. For example, not all WiFi channels are used in residential WiFi or a high-density environment; there are a large number of access points(APs). This causes an underutilization of these precious spectrum resources.

Furthermore, according to the requirement of the Harmonized European Standard in ETSI EN 301 893 Vl.7.1 (2012–06), LBT grants performing a clear channel assessment (CCA) prior to a new transmission and occupying the channel with limited duration after successful access in the load-based equipment (LBE).

They need to devise a plan and come up with ideas that enable the effective utilization of scarce resources. I am going to discuss a variety of strategies that will allow the cooperation of WiFi at 2.4GHz with WiFi at 5GHz and also the co-existence of WiFi at 5GHz with other wireless technologies like LTE-U and LAA. Therefore, a critical element of the design for LTE in unlicensed bands is to ensure LTE-LAA co-exists with current access technologies such as WiFi on fair and friendly bases.

All of that can enhance the utilization of these spectrum resources and optimize the system's performance.

The rest of the paper is organized as follows. Section II gives some basic background of the relative technologies. Section III discusses the internal coordination of the WiFi system. Section IV will cover the WiFi network coexisting with LET-U, while Section V presents the coexistence with LAA and some enhanced algorithms. Some ideas of cross-communication technology follow this in Section VI.

II. BACKGROUND

In this section, I will discuss the background of all the major technologies involved. First, I will discuss WiFi technology and its different standards, which are currently in use. Second, I will discuss LTE technology and its variant, which operates in the unlicensed frequency band, LTE-U. I will also discuss the different access mechanisms that these technologies use and their comparisons with each other.

1) WiFi networks: WiFi is one of the radio technologies based on the IEEE 802.11 standards. It is used for the wireless local area networking. The WiFi network can be an infrastructure network with a fixed central element (base station, access point). This kind of network structure has a common backbone. Meanwhile, it can also construct an independent network with which the elements in the network can directly connect (Ad-hoc network). Basically the WiFi system is a distributed network, the classic architecture is shown in the figure 1.

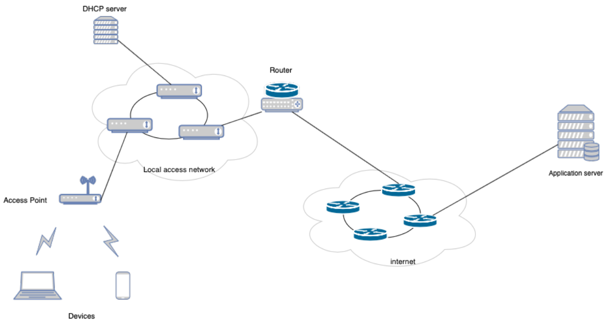

Fig. 1. Basic architecture of WiFi network

In Medium Access Control (MAC) of WiFi network, WiFi stations(STA) cannot detect collisions, when collision happens, it will waste the whole frame. To avoid collisions, I need to use some back-off procedures where a channel is reserved. I can have this capability by using a method called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). In CSMA/CA, the WiFi STAs will sense the channel before transmission, waiting for free medium and then transmitting the frame. It will send a short packet for channel reservation, which is called Request to Send (RTS) and Clear to Send (CTS). The sender uses RTS to check the receiver's availability. Once RTS is reached at the receiver side, if the receiver is idle at that time, it will reply with a CTS packet. Once the CTS packet is reached at the sender, the channel is reserved, and data can be transmitted reliably. If there is any collision, transmission will stop immediately. After waiting for a random back-off time, it will re-transmit. The key rule of the CSMA/CA is to back off before collision. The operation of the CSMA/CA is shown in the figure 2. In the problem of WiFi network resource sharing, I normally use the Distributed Coordination Function (DCF). When a station wants to transmit, DCF will require it to know the channel status for a DIFS interval. The CSMA/CA random back-off time is preventing the collision among the waiting time, it can be called contention window. DCF protocol is in principle fair, and it assume that the contention window is set a minimum value in first transmission and double up to a maximum value after each transmission failure[16].

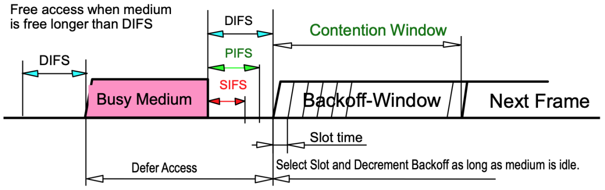

Fig. 2. Basic CSMA/CA operation

When the STA needs to connect to a WiFi network, it can search for a suitable channel using different methods, such as passive or active scanning. After finding the network, the STA should use a shared key (WEP) to authenticate and then associate it with an access point. The AP gives the STA an IP address through a DHCP server.

2) Coexistence LTE-U and 5GHz WiFi : Nowadays, with exponentially increasing data requirements, the frequency band of LTE has been extended from the licensed spectrum to an unlicensed spectrum. Meanwhile, this 5GHz available unlicensed radio band is initially used by WiFi 5GHz devices. It is well known that LTE is a communication standard that 3GPP has developed [1], and it uses a centrally scheduled mechanism to ensure performance in a licensed spectrum. By contrast, WiFi is built on distributed carrier sensing multiple access with collision avoidance (CSMA/CA), where the carrier sensing mechanism allows transmissions only when the channel is sensed as idle. Hence, due to the difference in the access mechanism between the LTE-U (centralized) and WiFi (decentralized), when both users of LTE-U and WiFi compete in the same unlicensed frequency band, the LTE-U users may occupy too many resources in the spectrum. It may also cause the WiFi 5GHz users to be unable to access the channel. Therefore, it is necessary to study the coexistence of LTE-U and 5GHz WiFi. In other words, a novel mechanism for this kind of coexistence, which is not harmful to the existing protocols, is needed.

To solve these problems, some approaches have been previously existing, and they can be taken into two main categories:

- LBT-based solutions
- Carrier Sensing Adaptive Transmission (CSAT) based solutions

With the LBT mechanism, when LTE-U users want to transmit, they must at first detect whether the channel is idle or not. If the unlicensed spectrum is busy, SBS will go back a period. However, the LBT scheme has several flaws. For instance, if there are multiple WiFi users in a dense environment, the LTE-U users will have rare opportunities to access the channel. Thus, the performance of coexistence will decrease significantly. There are also limitations for different markets, such as China and India, which are in the non-LBT market. Compared to LBT, CSAT-based schemes have gained popularity because they do not require any changes to existing LTE protocols. The CSAT mechanism defines a transmission cycle in which LTE-U only uses a part of the time interval for data transmission. In contrast, the duty cycle of transmission execution and transmission stop is the activity of other transmission systems in the cell. The degree is determined so that the sharing of channels and the quality of services can be ensured. They adjust the values to adapt and select the duty cycle. In this case, the performance can be optimized; meanwhile, the fairness of the coexistence of LTE-U and WiFi 5GHz may also be realized. Besides, 3GPP has not yet standardized LBT for LTE-U. In section 4, I discuss the non-LBT solutions in detail.

III. WIFI NETWORK COORDINATION

The IEEE 802.11 WiFi system operates on the unlicensed spectrum (ISM), and now mainly on the 2.4GHz and 5GHz frequency band. With the increasing WiFi devices and end-users, the 2.4GHz ISM band is already crowded, So the 5GHz band offers the opportunity in this scenario. In this section, I will focus on several scenarios of internal coordination of WiFi networks, where WiFi devices operating at different frequency bands can coordinate with each other, which can improve its system performance and the efficiency of spectrum utilization.

A. Challenges

The WiFi network is becoming crowded, in the real WiFi systems, massive end-user devices and access points(APs) connect into the WiFi system(figure 3), which I call density WiFi environment, it can cause the decreasing of the system performance[2]. Furthermore, the WiFi system has some problems that can degrade the system's efficiency. I will discuss them below.

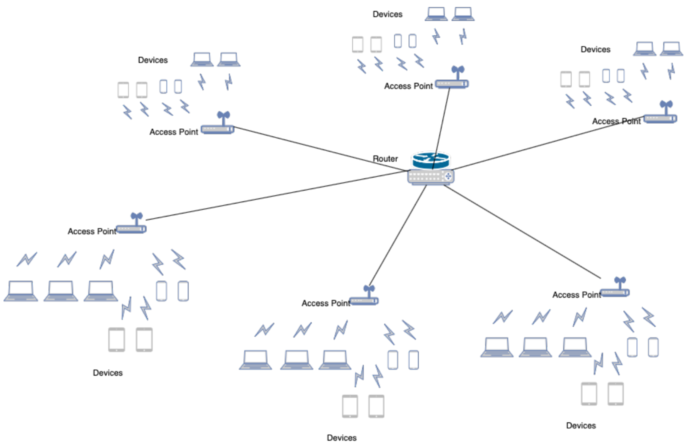

Fig. 3. Massive connection of WiFi system

1) Hidden terminal problem:

The hidden terminal problem is a much more difficult problem caused by WiFi devices than the direct channel competition[11]. When two nodes or stations will communicate with a wireless access point (AP), they can directly sense the AP, but cannot notice each other, this leads to difficulties in medium access control sub-layer. As shown in figure 4, when two stations(STAs) want to send a packet to the access point, STA1 sends a packet to the AP directly. Meanwhile, STA2 also wants to send a packet to the AP. However, it doesn't know that STA1 is sending the packet at the same time. This causes a collision.

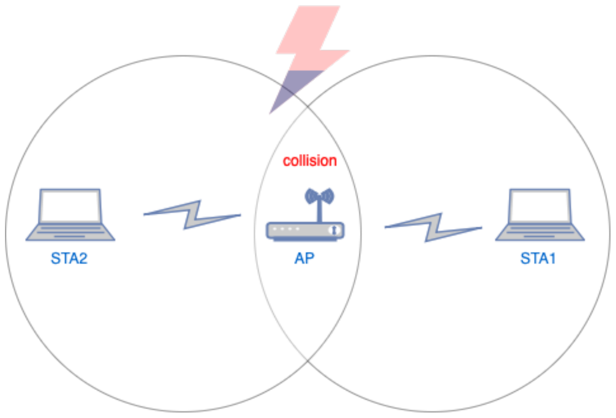

Fig. 4. Hidden terminal problem

2) Adjacent channel interference:

With more end-users in WiFi networks, they will occupy different channels. When there are too many APs arranged too closely, that means more than one adjacent channel is being used at the same time. For example, four channels can be used at the same time in the same area of the frequency, and several of them would be overlapping. In order to transmit more efficiently, it is better to let the APs communicate on non-overlapping channels.

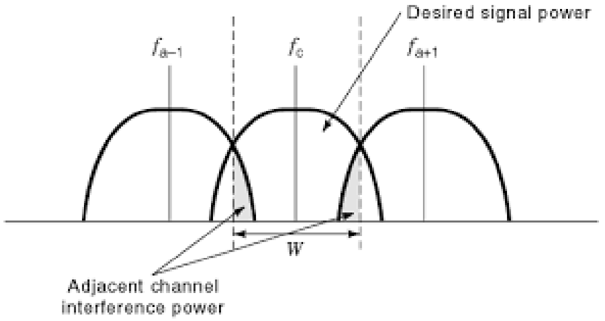

Fig. 5. Adjacent channel interference

Here, I have three closely arranged devices using Channels 1,2 and 3 (figure 6). Even if the transmission spectrum is perfectly shaped from the viewpoints of the standard or radio regulation, the received up-link packets at an AP from an STA can interfere directly with the adjacent channel interference (ACI) power from the closely arranged AP.[14]

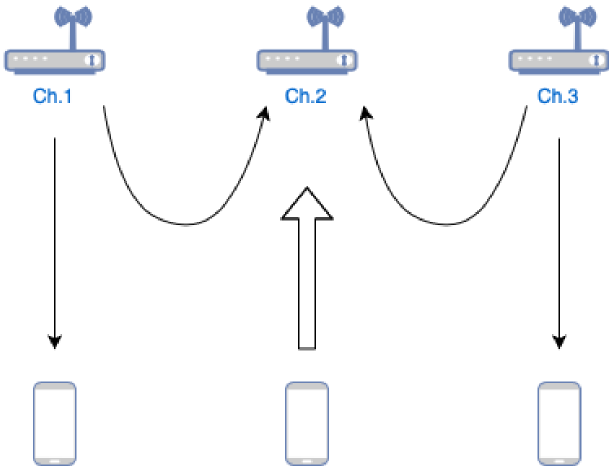

Fig. 6. Up-link packets interfered by the ACI from the closely arranged APs

On the other side, for the down-link procedure. Each AP will conduct the carrier sense before transmitting its down-link packets and determine if the channel is busy or idle. When the APs are closely arranged, the ACI power received at APs could reach the threshold level(figure 7). That could cause the malfunction of the carrier sensing procedure, even if the channel is actually idle. Thus, the AP needs to wait a random time to avoid "collision".

B. Solutions

The system's internal coordination could optimize the WiFi system. To provide an interference-free environment and, at the

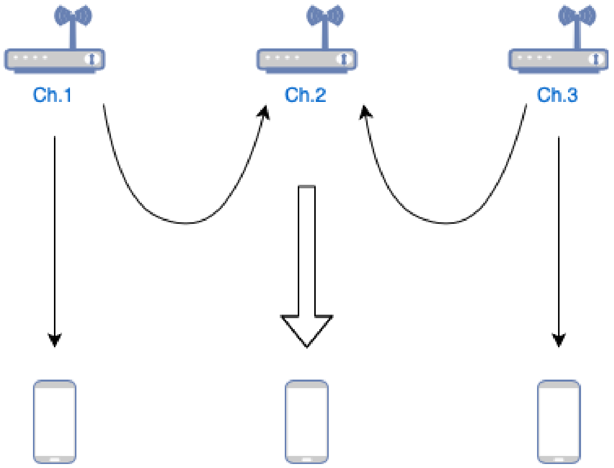

Fig. 7. Down-link packets disturbed by miss-decision of carrier sense due to the ACI from the closely arranged APs

same time, to get higher system performance, some suitable coordination strategies can be implemented. In this paper, I will discuss the following strategies:

1) Virtualization capable WiFi: Virtualization is a very important concept of network design in 5G networks; I could also consider implementing it in WiFi systems. There are two main methods in this scenario: Network Function Virtualization (NFV) and Software Defined Networking (SDN). NFV enables network functions that were traditionally tied to hardware appliances to run on cloud computing infrastructure in a data center. SDN is an architecture where the control and data planes are decoupled, network intelligence and state are logically centralized, and the underlying network infrastructure is abstracted from the application. Virtualization-capable WiFi is a centralized solution to optimize the WiFi network through internal coordination (figure 8).

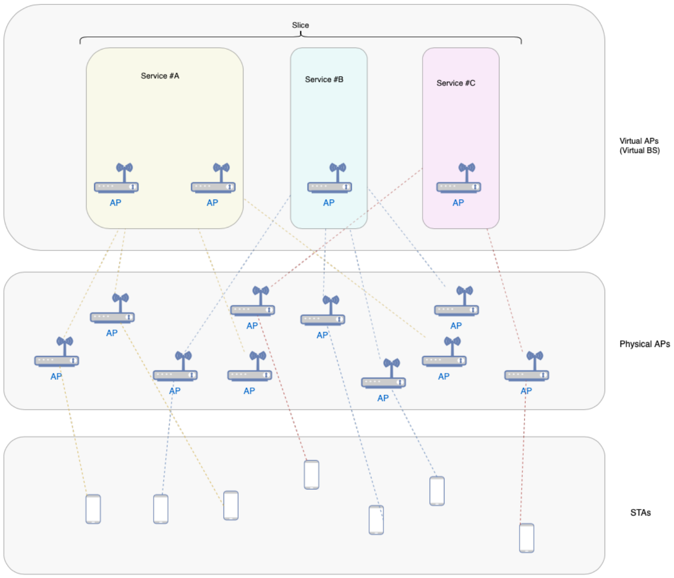

Fig. 8. the virtualization of WiFi network

a) Network Model: Very similar to 5G network, the virtualization of WiFi network is achieved by abstracting some parts of physically available WiFi network resources. That means building a virtual network on top of the physical WiFi networks regardless of their physical structure and allocating the independent parts called slices of resources only for a specific service or application. The management of servers or applications is fully programmable, such as making the configurations, the settings, and the algorithm to operate the abstracted resources.

b) Logical Model: In general, a logical integration approach could be used. That means multiple physical APs are logically integrated into a single virtual AP. They could act in coordination as one single AP. Virtual APs could be configured independently of the physical structure of the WiFi network. So when an STA connects to a physical AP, that means it associates with the virtual AP, which consists of multiple physical APs.

c) Dynamic Configuration: In a virtual WiFi system, I could use dynamic configuration to select channels and against probe request frames [9]. One example is shown in the figure 9. Each virtual BS works on only one single interface, regardless of how many physical APs it actually has. That could make the virtual BS configurable with the same MAC address, BSSID, and ESSID. All the beacon frames can be transmitted with the same beacon frame data. By controlling the virtual BS with the specific algorithm, the transmission channel within the virtual BS could be dynamically selected.

Probe request and probe response is a basic function in IEEE 802.11. To establish the connection, STA will transmit probe requests for target ESSID using different channels one by one. As shown in figure9, STA belongs to slice 2; in this procedure, vBS 2 responds to the probe request. Virtual BS 2 has two APIs, which operate on Channel 11 and Channel 7. The manager of vBS 2 knows which AP is occupied by fewer STAs and which channel has better performance, so AP 3 is chosen for the probe response.

In this way, closely arranged APs could have more chances to use a better channel without the ACI.

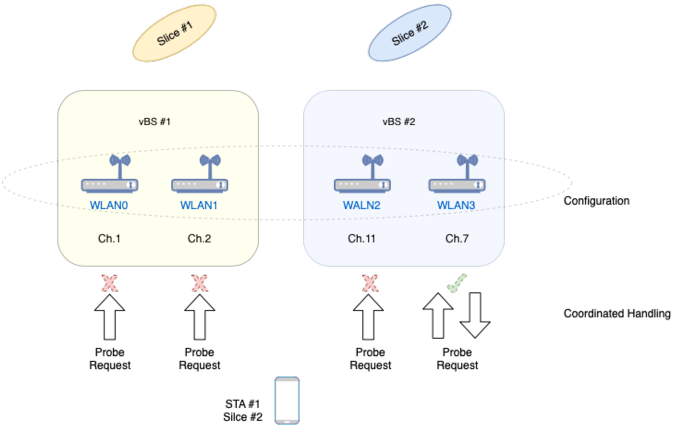

Fig. 9. Dynamical configuration

2) Radio Resource Management Based on Radio Environmental Maps: Radio Resource Management (RRM) is a data set of spectrum occupancy and interference levels computed based on raw spectrum measurements, propagation modeling, and spatial interpolation algorithms [12]. Radio Resource Management (RRM) algorithms can use Radio Environmental Maps (REMs) to optimize the overall network performance. REM is an essential technology that maximizes the usage of spectrum bands. The radio interference levels, propagation models, transmitter locations, communication parameters, and performances of the underlying communication devices can be processed using these distinct data. Furthermore, the REM data could provide insight into the interference management and coordination process for WiFi end devices, fostering optimal RRM in the ISM band.

In this paper I will not discuss more details about this scenario, there are some experiment in[6], and some other scenario to optimize WiFi system in [16],[8].

IV. COEXISTENCE OF WIFI 5GHZ WITH LTE-U

In the previous section, I briefly introduced the differences between LTE-U and WiFi mechanisms. In this part, I will first focus on LTE-U's mechanism and then find three sets of solutions from different perspectives, that is, how to connect LTE-U to the existing WiFi spectrum and how to make them work together to achieve efficient and fair coexistence.

LTE now supports a capability called carrier aggregation. It is intended to allow mobile operators to combine the various licensed spectrum bands they own into a single data connection between the user and the network. Licensed spectrum is highly efficient due to its exclusive occupancy of the spectrum, but the amount of available licensed spectrum can be limited and costly. In carrier aggregation technologies, the secondary cell, which is associated with LTE-U, has been used. However, I must consider the existing WiFi users in this band. If the interference can be detected in advance, the coexistence will be more efficient. The following Figure 10 which is from the paper[10], describes the scenario where LTE-U and WiFi are co-located. In this case LTE-U users only transmit in the UL and WiFi transmit simultaneously UL and DL in the BSS, thus, interference in the interactive area is generated.

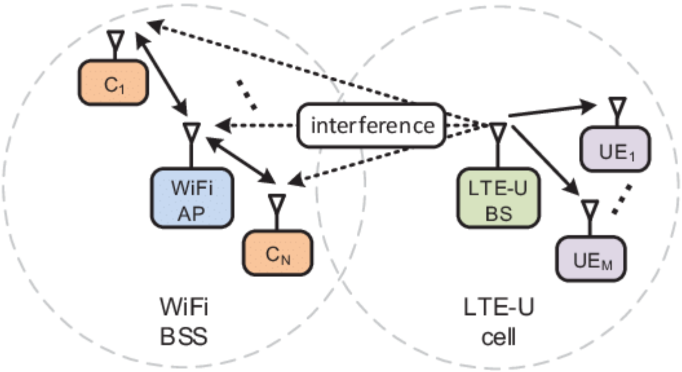

Fig. 10. WiFi BSS co-located with LTE-U cell[10]

Furthermore, I also consider coexistence from the perspective of WiFi. The coexistence of LTE-U and WiFi 5GHz sounds great for mobile network operators because it has a high potential to increase the capacity of existing LTE networks by utilizing existing infrastructures in the unlicensed band. However, WiFi operates at 802.11 standards, and it is designed to be a cooperative network. It is hard to ensure that WiFi will not be interrupted by LTE-U when it transmits in a coexistence scenario. In the following, I give a novel concept called HAP, i.e., hyper access point, as one kind of solution that can separately control the performance of WiFi and LTE-U compared with ordinary WiFi schemes.

A. Challenges

On a practical and theoretical level, executing the coexistence of LTE-U and WiFi 5GHz is a very difficult task. First of all, WiFi operates using DCF, which is based on CSMA/CA, to sense whether the channel is idle or busy in each time slot. When LTE transmission occurs, it is not able to estimate the transmission of WiFi. Before LAA, LTE-U duty-cycle does not carry out LBT, it can cause poor WiFi throughput performance in some conditions and high interference as well. In this section, I will mainly focus on these two challenges as following:

1) Fairness for Coexistence: The first challenge I face is, how to ensure fairness for the coexistence of LTE-U and WiFi 5GHz. When LTE-U and Wi-Fi networks coexist, Wi-Fi faces the situation of the channel not being accessed and the heterogeneous network having no channel to transmit messages. Therefore, achieving fair coexistence between LTE-U and Wi-Fi without reducing data throughput efficiency is a key issue that needs to be solved currently. Existing solutions such as CSAT (Carrier Sensing Adaptive Transmission) and ABS (Almost-Blank-Subframes) provide a guarantee of both efficiency and fairness. In the following part, I will also focus on other approaches.

2) Higher Efficiency: The second challenge I should solve is how to make the coexistence more efficient. To avoid WiFi being interrupted by LTE transmissions, I should set up a new coordination structure. The main idea behind this is that LTE-U and WiFi users work in a dynamic scheduling pattern. In the following solutions, I propose a new concept, namely HAP, which allows LTE-U to access the unlicensed spectrum of WiFi efficiently and can make good use of the cooperative mechanism of WiFi to allocate resources to different users and coexistence scenarios dynamically. Finally, the efficiency of the system will be greatly optimized. I will talk about it in more detail in the corresponding solutions.

B. Solutions

This section proposes three groups of coexistence design schemes to solve the coexistence problem between LTE-U and Wi-Fi.

1) HAP: HAP means a novel Hyper Access Point[3]. Unlike the traditional LTE-U mechanism, HAP can serve as both LTE-U SBS and WiFi AP as one node and operates as a kind of coordination pattern. It can utilize two standard WiFi MAC protocols, namely PCF (Point Coordination Function) and HCF (Hybrid Coordination Function). In a heterogeneous network, traditional APs and new HAPs operate on the same unlicensed spectrum. I can see this problem, i.e., how to allocate resources to different users and obtain a dynamic optimal allocation of CFP and CP. However, CFP means centralized cooperation, and CP stands for the traditional CSMA/CA mechanism. The following figure describes this HAP MAC frame. Each work cycle is divided into CFP and CP. In the CFP time slot, the beacon frame is sent first. Then, the LTE-U will be transmitted in the form of central control, while other LTE-U users and WiFi users temporarily stop transmitting until the start of the CP time slot, and the WiFi user starts transmitting.

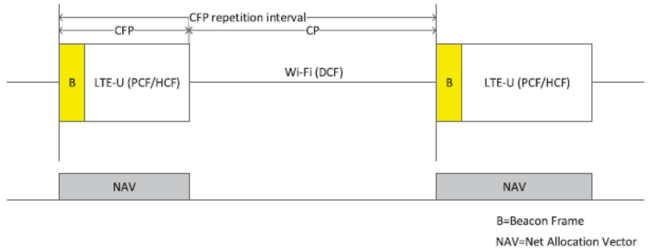

Fig. 11. HAP frame structure[3]

HAP has many advantages. For example, it is obvious that after different unlimited resources are allocated to different users, interference will be greatly reduced because the transmission of LTE-U and WiFi has been completely separated. They exist independently and do not interfere with each other. Therefore, the utilization and management efficiency of unlimited resources have been greatly improved. Besides, the flexible control of the duty ratio of coexistence.

2) Association Fairness: This scheme is similar to the previous HAP scheme, but more attention is paid to the beacon frame generation mechanism in different situations. Through the paper[13], I know that the maximum duty cycle of LTE-U on idle channels is 95 percent. When WiFi users want to share the same channel with LTE-U, they must first deliver a beacon frame as described in the previous solution. That's it. But even in a very long duty ratio, the OFF time is very short, so it is difficult to confirm whether the beacon has been successfully sent. In summary, it is necessary to establish correlation fairness, which is about the threshold of the duty ratio, the drop probability of the beacon frame, and so on. Through some mathematical analysis and model simulation, I can compare the throughput of the entire system in different situations.

3) Embedding LTE-U within Wi-Fi Bands: We have already discussed the coexistence mechanism of LTE-U and WiFi. Now, I discuss a new approach based on the WiFi perspective, which is to connect LTE-U to the standard WiFi protocol. This approach can greatly improve the fairness and efficiency of coexistence because it does not change the existing WiFi rules. The paper[4] proposes two different LTE-U access methods, namely UCA TD-LTEmode and standalone LTE-U Operation mode. In this section, I only discuss UCA TD-LTE, which is the LTE mode of unlicensed carrier aggregation time duplexing. As shown in the following figure, the entire process is divided into an association step and a data transmission step. In the association step, the HAP determines how and when to perform carrier aggregation. The process of carrier aggregation determines the allocation of LTE and LTE-U users. LTE-U users send a beacon frame at the beginning of each cycle, which contains very important information, the length of the CFP. After that, the LTE user will receive the control signal, and the UE can receive the unlimited resource signal.

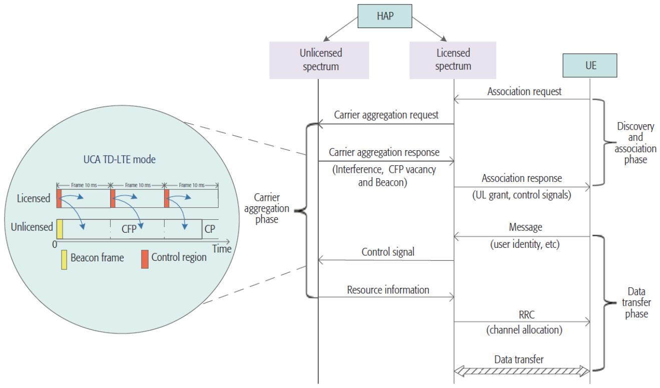

Fig. 12. UCA TD-LTE[4]

V. COEXISTENCE OF WIFI WITH LAA

A. System Model

I will focus here on the coexistence of LTE technologies with Wi-Fi technologies in the unlicensed spectrum 5 GHz. In LTE-LAA, the amount of data service exposure is the most important issue in transmission. The channel availability should be checked before the transmission to guarantee no huge transmission quality impact on other nodes over an unlicensed channel. As specified in [99], the file status in an eNB can be classified into two stages: the buffer state and the backoff state in an LAA system. In this work, I assume a non-saturated condition (the number of arrived files will never exceed the buffer size), which is more general and meaningful. In addition, the first come, first served (FCFS) algorithm is considered the stack protocol in this work [1010]. Furthermore, it is assumed that the traffic model for each base station is FTP-3, i.e., the arrival of request files follows an exponential process. Therefore, the probability Pk of k-th files entering the buffer can be expressed as:

$$P_k = \Pr(X = k) = \lambda \exp^{-\lambda k}, \tag{1}$$

Where, λ is the file arrival rate of the eNB.

[15]

As I need to model this problem, the file access activities in an LAA eNB are summarized as a Markov chain model in Fig. 13. A file status transits from the buffer state to the backoff state (from T1to bi) when the eNB schedules it. A backoff counter w for the file is firstly generated in the range [θ,CW($-$)1], randomly fulfilling the uniform distribution. That means the file has the same probability of dropping into the state bi, where i $\in$[θ, CW-1]. In the backoff state, the equipment shall perform a CCA check to observe the channel availability. If the channel is checked as free, the backoff counter can be decreased by 1 (i.e. the file status moves from bi to bi-1). Otherwise, the backoff number maintains the same value since other nodes occupy the channel. The transition probability of this process is assumed to be p, which is related to the collision rate and is determined by many factors, such as the number of competition nodes, the channel condition, and the traffic demand of a given node. In this contribution, I assume that backoff transition probability p can be approximated by the channel occupancy rate or sensing results of a given node. For instance, if a historical sensing result of a node is that with 80 percent of the case, the channel is sensed as free, and with 20 percent of the case, the channel is sensed as busy. In this case, p can be approximated to be 4/5. [15]

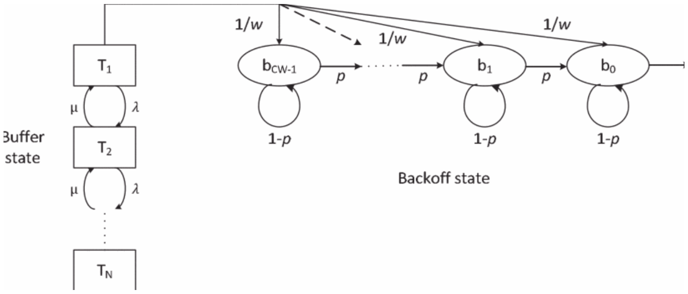

Fig. 13. Transition model of file activities in an enb.

Thus, the summarized transition probabilities in the whole Markov chain can be:

$$\begin{cases} P(\mathrm{b}_i|\mathrm{T}_1) = 1/w \\ P(\mathrm{b}_{i-1}|\mathrm{b}_i) = p. \\ P(\mathrm{b_i}|\mathrm{b}_i) = 1-p \end{cases} \tag{2}$$

In this condition, P(Y—X) represents the conditional probability of a transition from state X to state Y. The first equation in (2) indicates a file transits from the buffer state to backoff state, and T1 indicates the latest state when file is ready to be transmitted, w is the backoff counter. The second and the third equations in (2) indicate the transition probability of the backoff counter decreased by one or not, respectively.

B. Proposed LBT Procedure Enhancement

In this section, I elaborate on my designs for adjusting contention window size for the LBT procedure.

- Quality of service Metric Design In this part, I will talk about the average transition duration for the backoff counter. so at the beginning: The transmission latency is a very sensitive QoS index, especially when the real-time service is adopted. In the following, the approximated average transmission delay is deduced and considered as an example of the QoS metric. According to (2), the average transition duration for the backoff counter decrease by one can be calculated as:

$$\begin{aligned} t_{1-\text{backoff}} &= \lim_{n\to\infty}(p\cdot t_{\text{slot}} + p\cdot(1-p)\cdot 2t_{\text{slot}} + \\ &\quad p\cdot(1-p)^2\cdot 3t_{\text{slot}} + \cdots + p\cdot(1-p)^{n-1}\cdot nt_{\text{slot}}) \\ &= \frac{t_{\text{slot}}}{p} \end{aligned} \tag{3}$$

Where tslot is the CCA observation time.
Since the backoff countered w is uniformly generated in the range [0,CW1]. The average time spent on backoff state can be calculated straightforward:

$$t_{\text{All}-\text{backofff}} = (\frac{t_{\text{slot}}}{p}\cdot\frac{\text{CW}}{2}), \tag{4}$$

Where CW is the contention window size, it can be concluded that the average time spent in the backoff state is proportional to CW size and inversely proportional to p.
With the above assumptions, the file connection activities can be modeled as a MIMII queuing system. According to [11], I can conclude that the average time spent in the system is Ws=1 Here, is the file arrival rate, and is the system service rate. In this assumption, the service rate is related to the backoff delay and the file transmission time and can be calculated as:

$$\mu = \frac{1}{t_{\text{transmission}} + t_{\text{All}-\text{backoff}}}. \tag{5}$$

Furthermore, the average time spent in the system of a file can be expressed as:

$$W_s = \frac{1}{\mu-\lambda} = \frac{1}{\frac{1}{t_{\text{transmission}}+(\frac{t_{\text{slot}}}{p})\cdot\frac{\text{CW}}{2}} - \lambda} \tag{6}$$

For the same type of traffic, the average time spent in the system Ws, which can also be considered the average transmission delay, should be maintained at the same level in order to achieve file connection fairness among different nodes. In this work, the average transmission delay related to the contention window size, as shown in (6), is considered the QoS metric. [15]

- **Adaptive Contention Window (CW) Size Adjustment** By gathering the Quality of service (QoS) metric information from neighbor nodes via the X2 interface, the node is able to adjust its CW size to achieve service fairness. For example, it is assumed that node A and node B share the same spectrum resource and have the same type of traffic. If node A approximates its average transmission delay to be 50 ms, and node B approximates its average transmission delay to be 600 ms. By exchanging this delay information, node A finds that it performs far better than node B. If a desirable QoS is already achieved by node A, node A could enlarge its contention window value to release some resource to node B so as to achieve fairness between these two nodes. At the same time, node B notices that it does not work in a good situation, it decreases the contention window to grab more channel access opportunity. Furthermore, the QoS metric can be classified into multiple levels due to a limited number of exchange information. For instance, the transmission delay can be cataloged into eight levels, i.e., 3 bits of feedback information. The Nodes that are content on the same channel aim to approach the same level of QoS, as shown in Fig. 14.

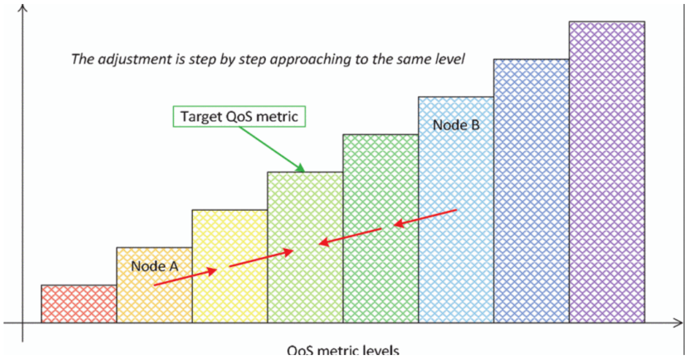

Fig. 14. Procedure of contention window size adjustment.

It has to be mentioned that the CW adjustment should be a semi-static and smooth procedure since slight contention window size adjustment will affect the channel competition result of all contenders, and the communication via the X2 interface is a relatively slow behavior. For instance, the CW value of each node can be updated every second or tens of seconds, which depends on the speed of information exchange.[15]

Furthermore, a gradient-approaching algorithm is proposed for the CW size adaptive adjustment.

Firstly, a node collects the QoS metric from nearby nodes to design a target metric. The target QoS metric of a given node can be calculated by averaging all QoS metrics with the same traffic type. Take the average transmission delay as an example:

$$W_s^{avg} = \sum_{i=1}^{N} W_s(i)/N, \tag{7}$$

Where N is the number of neighbor nodes with the same traffic type, and Ws(i) is the approximated average transmission delay for node i. In addition, prioritized QoS should be considered in multiservice traffic; for example, real-time sensitivity service should have better QoS metrics than non-real-time service from a fairness point of view.

1) Then, each node compares its own QoS metric with the target metric. It selects an appropriate CW value to increase/decrease its own QoS metric approaching the target one as the following expression:

$$\begin{aligned} & if\; W_{s_i} < W_s^{avg} - \mathrm{TH} \\ & \qquad \mathrm{CW}_i = \mathrm{CW}_i + \mathrm{Step}; \\ & elseif\; W_{s_i} > W_s^{avg} + \mathrm{TH} \\ & \qquad \mathrm{CW}_i = \mathrm{CW}_i - \mathrm{Step}; \\ & else \\ & \qquad maintain\, \mathrm{CW}_i; \end{aligned} \tag{8}$$

Here, "TH" is a threshold that triggers the CW size adjustment, and "Step" is the adjustment granularity that controls the speed of the adjustment.

2) By adjusting the contention window size adaptively, the QoS fairness for multiple nodes can be finally achieved.

VI. CROSS TECHNOLOGY COMMUNICATION

In the previous sections, I have discussed multiple challenges and their corresponding solutions to make both LTE-U and WiFi coexist in a given scenario. In those solutions, I particularly discussed the possible changes in the basic workings of both these technologies, which will ultimately allow them to detect interfering signals and then efficiently use the spectrum.

Apart from those solutions, I am looking towards a scenario where heterogeneous technologies like WiFi and LTE-U can coexist and are able to communicate with each other. I have a possibility of establishing a communication channel between the interfering endpoints operating in different technologies but with the same frequency bands and then communicating with each other so that the interference can be reduced. There are some approaches discussed in the literature about communication among different technologies, but they generally target the communication between WiFi and other sensor network technologies like ZigBee [17], [18]. But I need a mechanism where I can enable WiFi to communicate with LTE-U. LtFi [7] provides a solution to make cross-technology communication possible.

LtFi is low in complexity and compatible with the WiFi COTS hardware. The only step required is to install a small software on the WiFi AP. LtFi provides the capability to detect the proximity of the nearby WiFi APs. Results from [7] also show that LtFi is able to perform even at a very low signal power level, i.e. -92dBm. It enables the LtFi to estimate the number of nearby interfering LTE-U BSs accurately.

A. *LtFi: Cross Technology Communication system between LTE and WiFi*

LtFi proposes a solution to set up a common channel among co-located WiFi and LTE-U networks. LiFi uses the LTE-U BSs to send the broadcast signals containing the connection and identification data using the air interface. WiFi access points get this data and use it to establish a bidirectional control channel.

B. *Challenges*

Currently, there is no possibility of a discovery component where the co-located WiFi APs and LTE-U BSS can detect each other's presence. The problem under consideration is to enable cooperation between co-located LTE-U BSs and WiFi APs operating in the same frequency spectrum, 5GHz.

To achieve the desired result, we face two major challenges. The first is to establish a common management plane between the heterogeneous technologies. The second is cross-technology proximity detection, i.e., to identify the network nodes suffering from performance degradation.

C. Solutions

The proposed solution in LtFi is to have an architecture where multiple WiFi APs and LTE-U BSs are located in the same area and use the same frequency spectrum. A WiFi AP can be at the intersection of multiple LTE-U rings or only in the vicinity of a single LTE-U BS.

LtFi enables these distinct endpoints to communicate with each other through the protocols, which I will discuss in the upcoming sections.

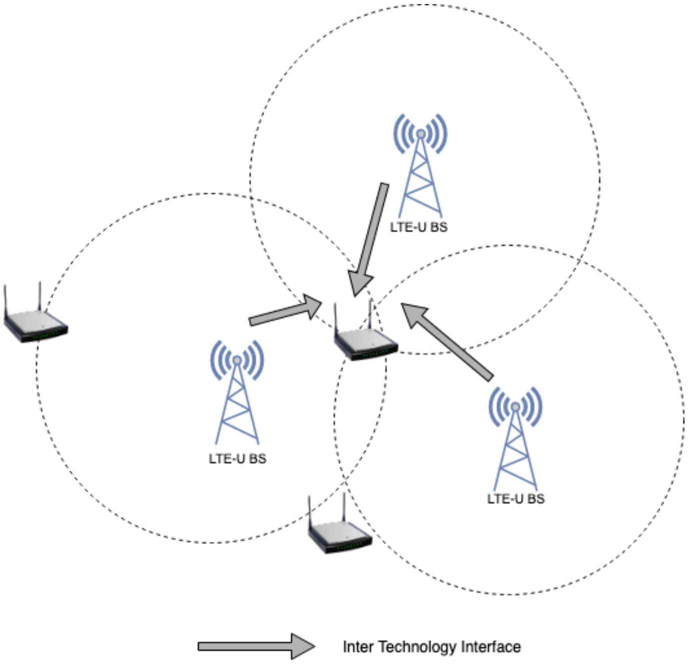

Fig. 15. LtFi - System Model

D. System Architecture

This section explains the architecture of LtFi. LtFi consists of two major components, which are as follows,

- LtFi - Air Interface
- LtFi - X2 Interface

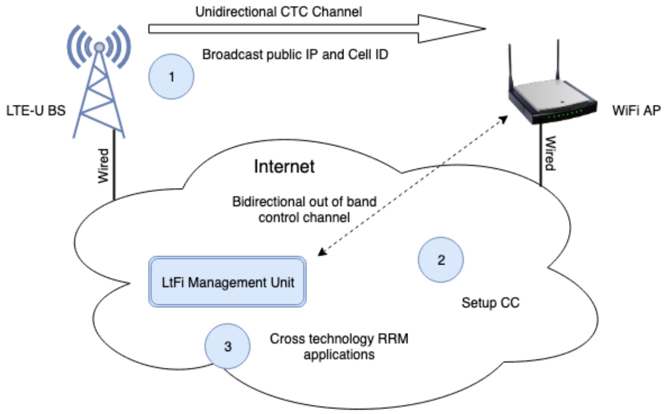

Fig. 16. LtFi - System Architecture Diagram

The LtFi air interface is used to establish the initial communication channel between LTE-U BS and WiFi AP. As shown in the figure, 16, the LTE-U station uses the air interface to send the configuration data, which is then used by the neighboring WiFi APs. The configuration data includes the global IP address and the cell ID. LtFi makes use of sub-frame puncturing to insert the data to establish the cross-technology channel. On the WiFi side, it monitors the Mac state so that it can differentiate between the WiFi and non-WiFi signals. The same interface is also used for proximity detection.

The LtFi—X2 interface is used to establish a two-way connection between the corresponding LtFi management unit and WiFi APs over the Internet. Once the two-way connection is established, the connected endpoints can share information about the spectrum and interface management.

1) Takeaways: LtFi solves the communication problem among the heterogeneous technologies but proposes to set up a cross-technology channel between participating LTE-U BS and WiFi AP. LtFi is simple to use and works very well with the existing WiFi hardware. The only requirement is to install a small piece of software on the WiFi AP. It requires a simple interface to the LTE-U eNb to send the configuration data to the neighboring WiFi node, which the WiFi AP later uses to establish over the internet channel with the corresponding LTE-U BS to perform interference and radio resource management.

VII. CONCLUSIONS

In this paper, I discussed the WiFi in general, which operates at 5GHz. How can I make the WiFi coordination? We further discussed the LTE unlicensed technology operating on 5GHz and the challenges it puts in coexistence with the WiFi devices working in the same band. By using the Virtualization scenario, the throughput performance of WiFi systems could be improved. This kind of internal coordination of the WiFi network could allow the system to operate dynamically. The optimized network could adjust different use cases and different network environments. By using the almost-blank sub-frames (ABS) feature to blank a certain fraction of LTE transmissions, WiFi throughput can be effectively increased. In addition to it, a kind of “coordinated structure” should be set up. This is higher-level management of spectrum access between the two systems. I further discussed the cross-technology communication between both these technologies in order to make the co-existence and coordination easy for the participating technologies.

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