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Wi-Fi and LTE-LAA Coexistence Problems, Challenges and Features in 5GHz Unlicensed Bandwidth

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Abstract

The demand for high data rate and stable quality of service from cellular networks' subscribers is a huge challenge for cellular operators. To overcome this issue, while keeping high data rate and stable quality of service more bandwidth is required. The lack of licensed bandwidth and also its high cost make it hard for operators to overcome this issue. To find an effective solution and expand the capacity of cellular networks, operators have started deployment of Long Term Evolution (LTE) in unlicensed bandwidth, exactly utilizing 5GHz unlicensed bandwidth in small cell scenarios. The extension of LTE to the 5GHz unlicensed bandwidth where it is already in used by Wi-Fi will create huge coexistence problems between Wi-Fi and LTE. It results due to different channel access mechanisms of Wi-Fi and LTE. This paper presents the channel access mechanisms of Wi-Fi and LTE-Licensed Assisted Access (LTE-LAA), coexistence problems, challenges, privileges, coexistence features of LTE and Wi-Fi. Finally, simulations are provided for LTE-LAA based Listen Before Talk (LBT) mechanism and Wi-Fi to show that LTE-LAA with LBT mechanism is friendly to the Wi-Fi networks when using the same 5GHz unlicensed channel. The simulation results illustrate that LTE-LAA based-LBT channel access mechanism by alone cannot bring a fair coexistence between these two technologies, and it needs further improvement.

Keywords: LTE, LTE-LAA, Wi-Fi, Coexistence, LBT

1. INTRODUCTION

Based on the rapid growth of internet-based services, the cellular networks need to expand their capacity and respond to the demand of customers accordingly [1]. The cellular networks are facing huge capacity problems due to high load of traffic and the explosion of data hungry applications. As operators using licensed spectrum, due to the lack of licensed spectrum and its high price it will be difficult for operators to overcome the issue of capacity. As operators look for a supplementary

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best solution to offload their traffic. The only effective solution is to offload cellular network traffic and expand the capacity of unlicensed bandwidth by LTE [2].

Third Generation Partnership Project (3GPP) in Release-13 (R-13) started working on extension of LTE to the 5GHz unlicensed bandwidth. The use of unlicensed bandwidth by LTE will cause serious coexistence issues between Wi-Fi and LTE networks as they use different channel access mechanisms in their Medium Access Control (MAC) protocols. The existing channel access mechanism of LTE is an aggressive mechanism, if it operates in the same operating frequency with Wi-Fi systems; the chance of channel access of Wi-Fi users will be very low even zero when the number of users increase. 3GPP, to fairly share the 5GHz unlicensed bandwidth between Wi-Fi and LTE, they launched LAA[3] based on Listen Before Talk (LBT) channel access mechanism, a similar channel access mechanism to Wi-Fi [3]. LTE-LAA channel access mechanism is based on LBT, a similar mechanism to Wi-Fi Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA). In LBT channel access mechanism a transmitter will first listen to the channel for a Clear Channel Assessment (CCA) time interval, if the channel is available for CCA time it will send the data, otherwise it will select randomly an Extended-CCA (ECCA) as a back-off time.

The unified structure of the LTE core network for both licensed and unlicensed bandwidth will help the operators to guarantee the valid authentication, high mobility and guarantee Quality of Service (QoS) to the users. In LTE-LAA the unlicensed bandwidth will be used only to increase the data rate in the downlink (DL), but the uplink (UL) and control signal will be carried in licensed bandwidth.

This research study will act as unique point where it will help the researchers and other interested concerns to find coexistence related factors and features related to these two technologies. The study gives an overall idea about the coexistence of LTE-LAA and Wi-Fi.

The rest of the paper is arranged as follows: In part 2, the channel access mechanism of both Wi-Fi and LTE-LAA is explained. In part 3, problems and challenges towards coexistence of Wi-Fi and LTE-LAA are provided. In part 4, coexistence features of both technologies are presented. In part 5, the performance differences of the two technologies are discussed. In part 7, performance degradation of both technologies is reviewed. In part 8, Wi-Fi and LTE-LAA simulation models are given. In part 9, the conducted simulation results are discussed. In part 10, findings and suggestions are found. In part 11, conclusion is given.

2. CHANNEL ACCESS MECHANISMS

2.1. Channel Access Mechanism of Wi-Fi

In Wi-Fi network, medium access of Wi-Fi network station is more complex than a wired one. The station in a Wi-Fi network is unable to detect a collision during its transmission, while sharing the same transmission medium with other stations. The Wireless Local Area Networks (WLANs) are half duplex systems. Therefore, a station cannot transmit and detect the collision at the same time [4].

The 802.11 standard introduced two common MAC protocols, a contention-based, Distributed Coordination Function (DCF) and non-contention based, a centralized protocol, Point Coordination Function (PCF). PCF mechanism is a centralized channel access mechanism. In PCF, the access point (AP) sends the polling message to one station. The station after receiving the polling message from the AP can transmit. The AP when receives the feedback from station, will continue polling another station. In PCF, if a station does not have data to transmit, it will respond with a NULL message to the AP, which causes waste of resources. Even worse, when the number of stations

[3] In this study the LTE-LAA and LAA is used interchangeably

increase in the network, the waiting time for stations to transmit their packets will be also increased due to polling process. PCF mode is not a common mode. Mostly the DCF mode is set as a default MAC protocol.

2.1.1.DCF Channel Access Mechanism

DCF is a non-centralized contention-based mechanism. DCF uses CSMA/CA. The station is only allowed to send the data when it senses the channel and find it free. CSMA/CA uses two channel access methods. Basic and request to send/clear to send (RTS/CTS) methods [5]. The basic approach is a two-way handshaking method. While RTS/CTS as shown in Figure.1 is a four-way handshaking method. In basic approach, the sender will send the Acknowledgement (ACK) frame with original data to the destination. When the receiver gets the data correctly, it will respond back to the sender with confirmation ACK. Hence it will complete the two-way handshaking process. In the RTS/CTS, the sender sends RTS frame to the receiver. If the target user correctly receives the RTS frame and is eligible for receiving, it will respond back to the sender with a CTS frame. The sender after receiving the CTS frame, will send the data frame to the receiver. The receiver after receiving the transmitted data correctly, it will accept the transmitted data frame as a received data frame. Thus, the four-way handshaking is completed.

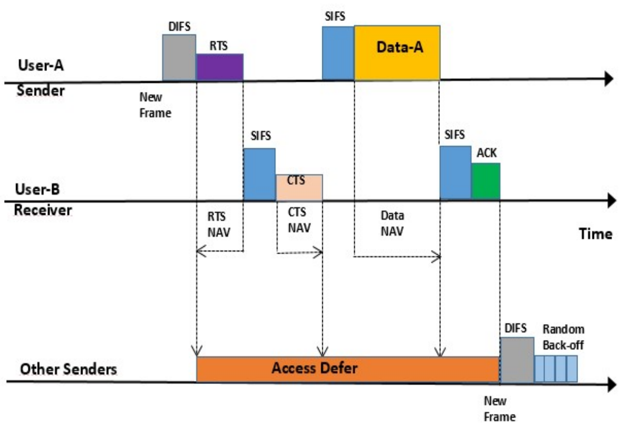

Figure 1. DCF based channel access mechanism

In the second (RTS/CTS) method, if the sender does not receive a CTS frame after sending an RTS frame, RTS/CTS tries to repeat the retransmission process. Network Allocation Vector (NAV) performs virtual carrier sense mechanism [6]. In NAV, each transmitting frame holds a duration value, which specify the required conversation period for a station.

The Figure.2 depicts the flowchart of the CSMA/CA mechanisms. When a station has a new frame to transmit, first it will sense the channel for distributed inter-frame space (DIFS) interval, if the channel is free for DIFS interval it will send the frame immediately, otherwise, the station will postpone its transmission. Again if the channel is sensed free for DIFS interval, the station will select a random back-off number B to further postpone its transmission based on selected random number. The random back-off number or B is selected between (1, CW). The selected random back-off number is decreased by one when the channel is sensed idle for each slot time. The B is frozen when the channel is sensed again busy, and is resumed when the channel is sensed idle again for DIFS interval. When the B reaches zero, the station will transmit the frame. When the receiver receives the frame correctly, after a short inter-frame space (SIFS) interval it will send the ACK frame to the sender to confirm the correct reception of the frame. If the sender receives the ACK message after a SIFS interval, subsequently it will start for a second transmission, otherwise, the sender will start the retransmission procedure for the lost frame.

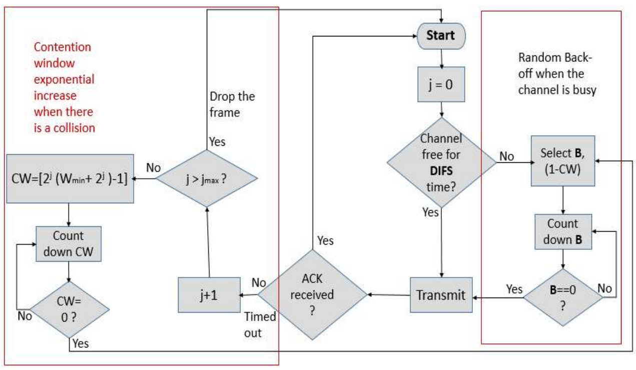

Figure 2. CSMA/CA transmission processes

When there is a time out for ACK frame (sender does not receive the ACK frame after SIFS interval) the sender will start the retransmission procedure. The retransmission procedure is based on contention window (CW) window exponential increase. CW= $[2^j (W_{min}+2^j)-1]$, CW_{min} = 15 and CW_{max} = 1023 and the exponential increase is as (15, 31, 63 ……1023) [7]. j is the number of retransmission and j_{max} is the maximum number of retransmission. When the frame is lost, it means a collision is occurred during the transmission and retransmission procedure will be activated. Each time when there is a collision, the sender will perform a retransmission procedure. The retransmission procedure is repeated until the retransmission number reaches to its maximum number, and after the maximum retransmission if there is again a collision then the frame will be dropped.

2.1. LTE-LAA Channel Access Mechanism

The LTE-LAA standard is introduced by 3GPP in R-13 [8]. The LTE-LAA is an extended version of LTE to the unlicensed bandwidth. In order to provide improved services to the users, LTE-LAA aims to use both licensed and unlicensed bandwidth. LTE-LAA uses carrier aggregation (CA) technology to serve in both licensed and unlicensed bandwidth. The primary cell (Pcell) uses licensed bandwidth which will provide better QoS, mobility and reliability to the users. On the other hand, higher data rate will be provided using unlicensed bandwidth as an additional carrier. LTE-LAA uses the LBT mechanism to share the same channel with other technologies. Where the Node (user) first will listen to the channel for a CCA interval, if it finds the channel clear/free for a CCA time interval, then it will start the transmission. Otherwise, it will select a random back-off until the channel becomes free. Figure.3 shows the channel sharing procedure of LTE-LAA with Wi-Fi. The LTE-LAA is a global standard that aims to provide a single solution to meet legal requirements in all regions [8].

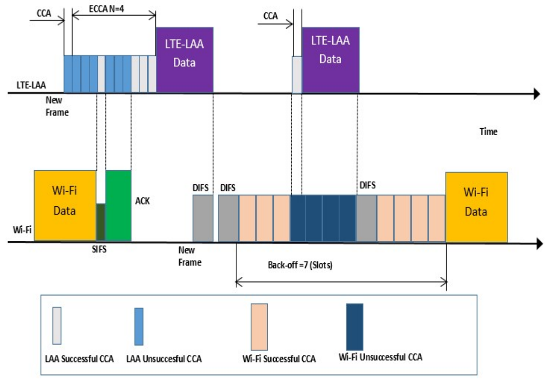

Figure 3. Joint LTE-LAA and Wi-Fi channel access mechanisms

For further clarification the working mechanism of LBT mechanism is shown in Figure.4. The Node will first listen to the channel for CCA interval, if the channel is free for CCA interval it will start the transmission, otherwise, it will select a random back-off number N, an extended-CCA (ECCA). It will count down the N until the N reaches to zero. When the N reaches to zero the Node will start the transmission. After transmission it will take the nack (negative acknowledgement) from hybrid automatic repeat request (HARQ), to see if there is collision during the transmission or not. The collision probability in LTE-LAA is based on HARQ feedback [9].

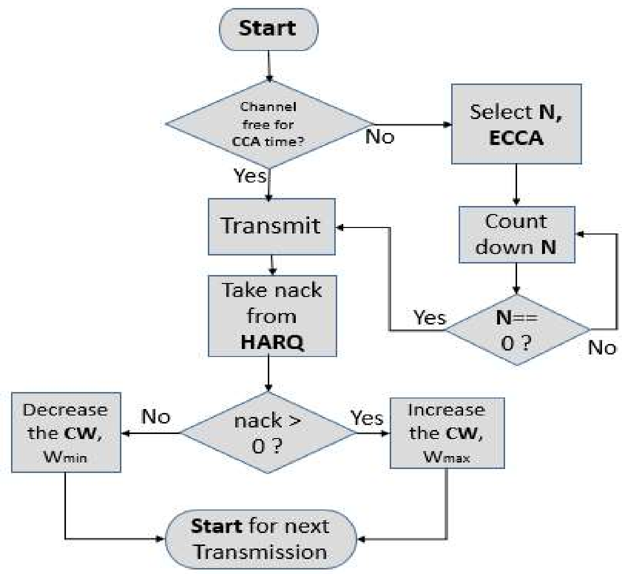

Figure 4. LBT processes for LTE-LAA [10]

The CW is updated based on HARQ feedback. If there is a nack from a recent transmission, the CW will be increased to the maximum, otherwise, the CW will be reset to a minimum and the Node will start for next transmission. The duration of the transmission opportunity (TXOP) depends on the class of CW size. There are four classes of CW [11].

3. Wi-Fi AND LTE COEXISTENCE PROBLEMS AND CHALLENGES

The huge challenge for LTE and Wi-Fi coexistence is that when the LTE uses the same channel in the existence of Wi-Fi, as Wi-Fi uses CSMA/CA channel access mechanism, Wi-Fi users will suffer from high performance degradation. From the other hand, the performance of LTE is almost unaffected. This results from that these two technologies have not the same channel access mechanisms. LTE is designed as a specific controller of a particular bandwidth. LTE transmits the data simultaneously with no delay due to its aggressive channel access mechanism. On the other hand, Wi-Fi is designed using CSMA/CA and a random back-off to fairly coexist with other technologies. Thus, Wi-Fi stations will have little chance of transmission because of its friendly channel access mechanism when sharing the same operating frequency with other technologies.

The lack of inter-technology coordination and mutual interference management mechanisms are the most serious coexistence challenges towards Wi-Fi and LTE technologies. Most broadband wireless access technologies have an interference management mechanism. However, they are used for interference management of their own terminals [12]. These interference management mechanisms cannot respond to the inference issues in heterogeneous wireless networks. Today, the most widely used wireless networks, LTE and Wi-Fi are not only different from each other's, but they are also incompatible when sharing the same operating frequency.

Another problem is the LTE model for deployment of small cells in unlicensed bandwidth as regulatory restricted the effective isotropic radiated power (EIRP) in unlicensed spectrum is too lower than those used in LTE licensed macro cells. In addition, LTE should be able to determine a fair coexistence mechanism when sharing the same unlicensed operating frequency with Wi-Fi networks [12].

The ambient interference in 5GHz unlicensed bandwidth is another serious issue for LTE extension to the 5GHz unlicensed bandwidth. 5GHz unlicensed bandwidth already in used by some other technologies such as Wi-Fi and weather radars. Beside this, Unlicensed-LTE (U-LTE) technologies (LAA, LTE-U and MulteFire) also intended to operate in the same bandwidth. Hence these technologies can have certain interference to each others. The regulatory to fairly use the 5GHz unlicensed bandwidth and reduce the Radio Frequency Interference (RFI) from other Radio Access Networks (RANs) to its minimum they considered some deployment rules and requirements [13]. As U-LTE technologies also intended to use 5GHz unlicensed bandwidth they need to adhere to those rules and requirements same as Wi-Fi. For example, the channels 120-128 in the same time also used by weather radars, the regulatory requirement in some regions such as Europe and Japan to use these channels is to observe the Dynamic Frequency Selection (DFS) and Transmit Power Control (TPC). The Wi-Fi or U-LTE when use these channels and receive the signal from weather radar they must dynamically change the channel. However, this will interrupt the transmission. The interrupt maybe unnoticeable for the non-real time applications such as mail and web browsing, but will certainly have an impact on latency sensitive, real-time applications such as voice and video calls.

In [14] they evaluated the performance of Wi-Fi, LAA and LTE-U in 5GHz unlicensed bandwidth. Based on their simulation results Wi-Fi is found a good neighbor to LAA and LTE-U. In the same time when LAA and LTE-U coexist their performances are similar. Particularly, LTE-U has better performance when coexist with LAA and Wi-Fi than with LTE-U itself. From other hand, in term of channel occupancy, LAA and LTE-U have more chance of channel occupancy than Wi-Fi. Hence, the performance of Wi-Fi degrades when coexist with LAA and LTE-U.

The study in [15] evaluated the ambient inference effects in 2.4GHz for Wi-Fi networks. They evaluated the impact of six non-Wi-Fi devices (Microwave oven, Bluetooth headset, Analog cordless phone, Digital cordless phone, Analog wireless video camera and Wireless jammer) on Wi-Fi performance. In the presence of these non-Wi-Fi devices the performance of Wi-Fi is certainly affected. This affection is more serious when the non-Wi-Fi devices are found in a near distance to the Wi-Fi networks.

4. COEXISTENCE FEATURES

In below section some of the coexistence features of both technologies are reviewed.

4.1. MAC Protocols

A centralized MAC protocol is used by LTE. It includes a dynamic resource scheduler, which allocates resources dynamically. When the scheduler shares resources between mobile devices, the traffic load, the required QoS, and the status of the channel are taken into account. From other side, Wi-Fi's MAC uses CSMA/CA as a channel access mechanism. Therefore, Wi-Fi systems will be highly affected when LTE starts operating on the same operating frequency without any fair coexistence mechanism.

4.2. Motivation of Sharing the 5GHz Band by Wi-Fi and LAA

The existing cellular networks are facing with huge capacity problems. The promised benefits of the Wi-Fi and LTE networks coexistence has attracted the attention of the researchers [16]. LTE-LAA will provide high data rate and good coverage to the cellular users. From other hand, if a fair coexistence is not found between these two technologies when they share the same operating frequency, traffic load, contention for channel access and network congestion will be increased. The reason to deploy the LTE-LAA in 5GHz bandwidth is not to withdraw the Wi-Fi system, but to further improve utilization of the 5GHz unlicensed bandwidth. To efficiently integrate LTE and Wi-Fi networks, there will be reasonable advantages for both sides. From one side, Wi-Fi networks use only unlicensed bandwidth, the contention of users for channel access causes of low efficiency. Thus, shifting some of the traffic to a well-controlled network (LTE) is needed. From the other hand, to decrease the interference and congestion of the existing LTE network, it is possible to shift a huge amount of the LTE network traffic to the Wi-Fi 5GHz unlicensed bandwidth by deploying LTE-LAA in small cell scenarios.

4.3. Combination of Licensed and Unlicensed Bandwidths

When there is a demand for more capacity, carrier aggregation can be used to manage different capacity carriers. Based on CA deployment mechanism one carrier will serve the Primary Cell (Pcell) and other carriers will serve the Secondary Cells (Scells) [17]. Hence, the second carrier will be only supplemental downlink (SDL) carrier. SDL will be used as a secondary data transmission carrier in downlink, but the uplink and control channel will remain in the licensed bandwidth.

4.4. LTE Carrier Aggregation with Unlicensed Bandwidth

In order to achieve high data rate, it needs to increase the number of carriers, and it is only possible by using CA technology. LTE-Advanced (LTE-A) have started using more than one carrier in the single transmission and CA is the only possible way to use more than one carrier in a single transmission [18]. Therefore, carrier aggregation is one of the most important features to ensure that LTE-LAA technology can use both licensed and unlicensed spectrum together.

4.5. Stable Quality of Service (QoS)

It should be noted that only unlicensed spectrum-based transmission is not stable. Because using only unlicensed bandwidth makes it is difficult to insure acceptable QoS and stable transmission. Therefore, it is not advisable to ignore the use of the licensed bandwidth when extending the LTE to the unlicensed bandwidth. To provide the users to use both spectrums (licensed and unlicensed) LTE-LAA was introduced by 3GPP in R-13.

5. PERFORMANCE DIFFERENCES

Mobile operators evaluate LTE-LAA in 3GPP standardization. Deploying LTE in the unlicensed band can often face a confused decision whether to deploy Wi-Fi or LAA when planning for using small cells (SC) topologies. Considering some practical commercial factors in some deployment scenarios, Wi-Fi or LAA must be used by alone in 5GHz band, regardless of any coexistence mechanism. Some factors that indicate the performance difference between these two technologies are given in below.

5.1. Spectral Efficiency

The following given factors determine LTE-LAA spectral efficiency over Wi-Fi:

5.1.1. Interference Management

Initiative coordination and interference avoidance mechanisms, named, Enhanced Intercellular Interference Coordination (eICIC) and Coordinated Multipoint (CoMP), have been implemented in LTE to minimize interference and increase the spectral efficiency. CoMP transmission and reception refers to a variety of procedures that require coordination between geographically separated eNBs. Where a customer can be served with better resource allocation by multiple eNBs [19]. Hence, as LTE has a robust interference management systems, the management of interference in LAA will be much better than Wi-Fi.

5.1.2. Stable Transmission

As mentioned earlier, LTE implements the centralized MAC protocol. The resources are allocated centrally rather than contention based. For better resource allocation LTE uses the user channel quality feedback report such as channel quality indicator (CQI) and channel state information (CSI).

5.1.3. Good Coverage and Better Mobility Support

The users in LTE-LAA are operated in a single and joined architecture. The core network of LTE can be used for both types of spectrum. Joined architecture means the same core network for both macro and small cells user in licensed and unlicensed spectrums.

5.1.4. HARQ vs ARQ

The retransmission mechanisms in Wi-Fi and LTE are different. HARQ is used by LTE in the MAC layer, having higher efficiency than that of a single loop ARQ used by the Wi-Fi [20] . In ARQ, if there is an error in the received data (when it is detected by the ARQ), the receiver will request the sender for retransmission. In HARQ, however, when there is an error in the received data, the received data will be buffered and the receiver will request for retransmission of the only lost packets. Then receiver combines the retransmitted packet with the buffered data. When there is succeed decoding by receiver, it will respond with an ACK message to eNB.

5.2. Wi-Fi Privileges vs LTE-LAA

Wi-Fi has many benefits compared to LTE-LAA. Beside to its robust standardization and its established ecosystem, it is widely used and it possesses a wide AP foot print in public and business. This AP foot print can be used as a principle for the distribution and deployment of SC [21]. With the help of APs foot print the deployment of LAA small cells (SCs) can be speed up and also will decrease the cost and complication. On the other hand, an operator may face difficulties getting access to these services when combining the unlicensed and licensed LTE strategy because corporate and commercial places have their own Wi-Fi systems.

6. SUMMARIZING THE FEATURES DISCUSSED ABOVE

a) We found that Wi-Fi and LTE have different MAC adoption. In term of channel access procedure, there is no channel sense and a random back-off mechanism in LTE networks. Instead, LTE systems designed for licensed spectrum actually have a centralized control architecture that allocates a resource unit to the user in each sub-frame. In contrast, a Wi-Fi station that does not need a central controller, first it will sense the channel when there is a pending transmission. Moreover, for Wi-Fi systems it will only occupy the channel when the packets required to be sent.

b) Wi-Fi needs to improve the user mobility, coverage and network competence as LTE offers. LTE network is a well-managed and is properly integrated into the existing operator’s cellular networks. Hence, LTE offers valid authentication, stable transmission with guaranteed QoS [22]. Unfortunately, due to the various restrictions on Wi-Fi system, the above mentioned improvements seems hard to be achieved for Wi-Fi systems in the near future.

c) Wi-Fi deployment is easy and widely used in public and business. In addition, the introduction of LTE-LAA will now need to traverse a long journey as Wi-Fi performed. Based on the benefits of both technologies, the selection of LAA or Wi-Fi depends on environmental and also financial factors.

7. PERFORMANCE DEGRADATION

Many coexistence mechanisms are developed for Unlicensed-LTE (U-LTE). Such as, Dynamic Channel Selection (DCS), Carrier Sense Adaptive Transmission (CSAT) for LTE-U and LBT for LTE-LAA. When U-LTE and Wi-Fi share the 5GHz unlicensed bandwidth, these mechanisms were found useful for reducing interference and increasing the efficiency of spectrum utilization. The performance of each mechanism depends to the different factors such as network scale, traffic density, environment, deployment scenario (indoor, outdoor).

The simulation performed in [23], to assess the coexistence results of Wi-Fi and LTE in an indoor environment. Based on simulation results, when LTE shares the same channel with Wi-Fi, and there is no changes to the LTE channel access mechanism, Wi-Fi users seriously suffer from unfairness. By deploying 1 AP per system, LTE users lose only marginal performance (approximately 4% of basic performance), but on the other side, Wi-Fi has lost almost up to 70% of its performance. During the second density deployment, with deploying 5 AP per system, the performance degradation seen by Wi-Fi is around

100%. With increasing the density (APs and Users) channel is totally blocked for Wi-Fi users.

The work in [14] has observations similar to those in [23]. Specifically, by increasing traffic load of the network, it was found that LTE performance was only slightly degraded, but from the other side Wi-Fi performance was seriously dropped. Because Wi-Fi and LTE owned different channel access mechanism. When the channel is occupied, Wi-Fi will postpone its transmission, in contrary, the LTE will always prefer to transmit and in order to deal with high interference it will select a more efficient transmission approach. The aggressive channel access mechanism of LTE causes where LTE users use the major number of transmission opportunities and the Wi-Fi stations will remain in waiting and random back-off mode. By good fortune, the outcomes obtained in [24] showed that the harshness of this adverse effect on Wi-Fi systems could be effectively controlled by limiting LTE aggressive behavior.

The study in [25] presents the coexistence of U-LTE (LTE-U and LTE-LAA) and Wi-Fi in the 5GHz unlicensed bandwidth. Based on the simulation results LTE-U found more unfair to the Wi-Fi due to two factors. First, the incompatibility of LTE-U’s duty-cycle to Wi-Fi. Second, lack of an effective coexistence mechanism. Beside this, LTE-LAA with only LBT mechanism cannot guarantee a fair coexistence of LTE with Wi-Fi.

Here in this part we share our simulation results which we conducted for LTE-LAA and Wi-Fi, to find that how LTE-LAA with its LBT mechanism is friendly to Wi-Fi when they share the same 5GHz unlicensed operating channel. We used NS3 [26] with an available LAA and Wi-Fi coexistence model to conduct the results. Based on simulation results, the LBT mechanism which prescribed by 3GPP (European Regulatory) by alone cannot bring fair coexistence between Wi-Fi and LTE-LAA technologies. Still Wi-Fi users suffering from high latency and throughput degradation compared to LAA users.

8. Wi-Fi AND LTE-LAA SIMULATION MODELS

Indoor scenario is deployed for both operators. Each operator deploys four small cells. The four cells or base stations (eNBs for LTE-LAA and APs for Wi-Fi) are equally spaced in a fixed location. The simulation is conducted for two sets of density. First set of density, each operator deploy 5 users per cell, where the total numbers of users for both operators are 40 users (2 operators, 4 cell/operator, 5 user/cell, where total number of users for both operators, 2*4*5=40). In the second set of density, we increased (doubled) the number of users per cell for each operator (2 operators, 4 cell/operator, 10 users/cell, where the total number of users for both operator, 2*4*10=80).

a) Wi-Fi Model

Wi-Fi used 20MHz 802.11n channel. The energy detection threshold (ED) is set to -62dBm for detecting other Radio Access Technologies (RAN). Wi-Fi uses Binary Exponential Back-off (BEB) to update its contention widow (CW). The window (W) is set to (W_{min}=15, W_{max}=1023).

b) LTE-LAA Model

LTE-LAA uses LBT mechanism to fairly share the same 5 GHz unlicensed operating frequency with Wi-Fi users. The energy detection threshold is set same as Wi-Fi (-62dBm). LTE-LAA uses HARQ feedback for collision probability and also updating the CW as defined in [9]. The initial time for CCA is 43 µs, and the slot time of CCA is 9 µs. The maximum TXOP is 8 ms (based on CW window class). In LTE-LAA the collision probability is based on HARQ feedback, if 80% of feedback from recent transmission is negative (nack), the CW will be updated. The CW window is updated between 15-63 for LTE-LAA (W_{min}=15, W_{max}=63).

c) Traffic Model and Performance Metrics

The overall load is same (130Mbps) for both Wi-Fi and LTE-LAA. File Transfer Protocol (FTP) is implemented only for a downlink indoor scenario as recommended in [27]. File transfer rate is based on value of λ. The defined range for λ is between 0.5 to 2.5, here in this simulation, we considered the λ = 0.5. The performance metrics for latency (ms) and for data throughput (Mbps) is considered. The Table 1 lists the concern simulation parameters for both operators.

Table.1 Simulation parameters used for LTE-LAA and Wi-Fi

Parameters	Values
Scenario	Indoor
Number of cell/operator	4
Number of user/cell	5
Packet arrival rate λ	0.5
Traffic model	FTP over UDP
Frequency	5 GHz
Channel bandwidth	20 MHz
Channel High data rate	130 Mbps
W_{min} (Wi-Fi/LAA)	15/15
W_{max} (LTE-LAA/Wi-Fi)	63/1023
ED threshold (Wi-Fi/LAA)	-62 dBm
SIFS	16 µs
DIFS/CCA	50/43 µs
NACKs feedback (LAA)	80%
TXOP	8 ms
Slot time (Wi-Fi/LAA)	9 µs

9. SIMULATION RESULTS

The Figure.5 shows the latency impact for Wi-Fi and LAA users when they share the same 5GHz unlicensed channel. The simulation result is for the first set of density (40 users). The Figure.5 depicts that Wi-Fi users still suffer from high latency (waiting time) when they operate in the same channel with LTE-LAA users. More worse, when the number of users increase the latency (more for Wi-Fi users) also increase. The result for the second set of density (80 users) is shown in Figure.6. Result shows that by increasing the number of users, the latency will be also increased. But the increase of latency is seen much more in Wi-Fi side, Wi-Fi users suffer from a high non-fair coexistence latency. It is due to that when the number of users increase, the contention to access the channel also increase. As discussed earlier that Wi-Fi uses CSMA/CA an innocent channel access mechanism to fairly share the channel. But from other hand, LTE-LAA uses LBT as a coexistence mechanism which still has aggressiveness compare to the Wi-Fi CSMA/CA. Hence, Wi-Fi users loses more time to access the channel.

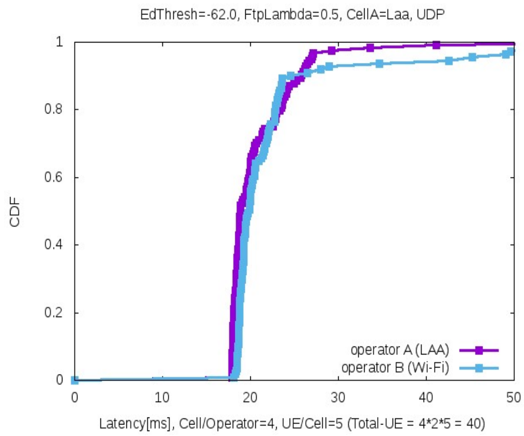

Figure 5. Wi-Fi and LTE-LAA latency (ms) based on LBT mechanism first set of density (40 users)

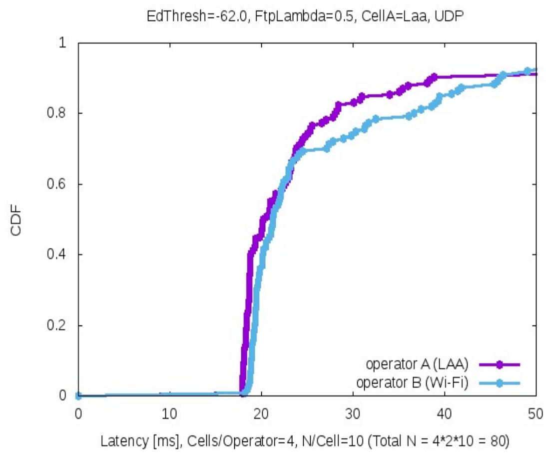

Figure 6. Wi-Fi and LTE-LAA latency (ms) based on LBT mechanism second set of density (80 users)

The second coexistence metrics is throughput. Figure.7 shows the impact of throughput degradation for both LTE-LAA and Wi-Fi users. As discussed in pervious section that Wi-Fi users suffer from high coexistence latency when they share the same unlicensed channel with LTE-LAA, in the same time also suffer from high data degradation as well. The Figure.7 shows that when the load in the channel increase, the throughput degradation for Wi-Fi users also increase. Same as discussed in previous paragraph, when the number of users increased the latency also increased, same for throughput, by increasing the number of users, the throughput degradation is also increased. The simulation result for the second set of density, where the number of users increased from 40 to 80 users is depicted in Figure No.8. The result obviously shows that when the number of users increased, the throughput degradation is also increased, and Wi-Fi users suffer from high non-fair throughput coexistence issue. In LBT mechanism the collision probability and CW size is updated based on HARQ feedback. The sub-frame associated to the HARQ feedback is received with a delay of 4 ms after its transmission [28].

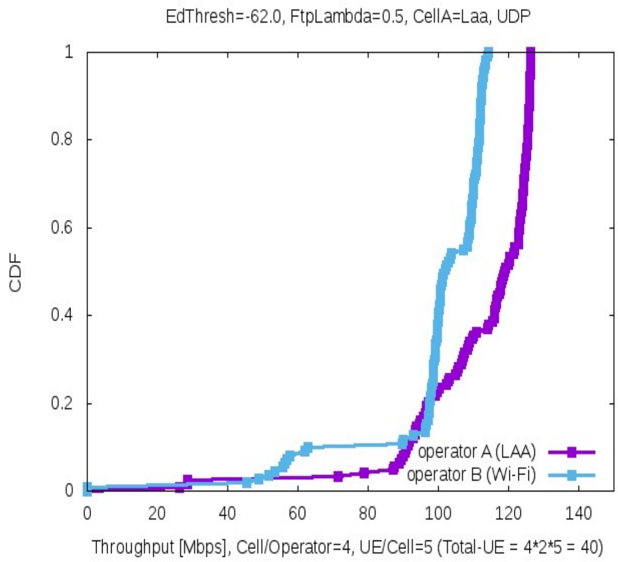

Figure 7. Wi-Fi and LTE-LAA throughput (Mbps) degradation based on LBT mechanism fist set of density (40 users)

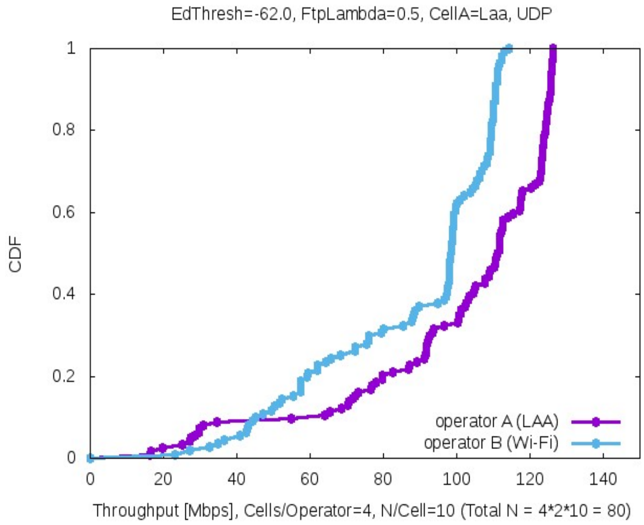

Figure 8. Wi-Fi and LTE-LAA throughput (Mbps) degradation based on LBT mechanism second set of density (80 users)

Hence, this is the main cause for having more collisions in the channel. When the number of collisions increase, both the latency and throughput degradation are also increased. Based on our simulation results and the results conducted in [29] the LBT channel access mechanism as prescribed by 3GPP by alone cannot bring a fair coexistence between Wi-Fi and LTE-LAA users, and still needs more improvement.

10. Findings and Suggestions

The main purpose of this study is to evaluate the coexistence problems, challenges and features of LTE-LAA and Wi-Fi technologies in 5GHz unlicensed bandwidth. In addition to evaluate the LBT coexistence mechanism that how it is friendly to the Wi-Fi. In below we summarize the main findings.

a) We understood if LTE when there is no changes to its air interface protocols coexist with Wi-Fi, Wi-Fi performance is seriously degraded. This is due to that Wi-Fi and LTE owned different channel access mechanisms in their MAC layers. Wi-Fi has an innocent channel access mechanism that sharing the channel fairly with other concern technologies, while LTE has an aggressive channel access mechanism designed to have always transmission opportunity.

b) To control the aggressive behavior of LTE and coexist in a friendly manner with Wi-Fi, 3GPP developed LTE-LAA technology. LTE-LAA uses LBT coexistence mechanism where the LTE air interface protocols are modified. LBT is a Wi-Fi CSMA/CA like channel access mechanism with channel sense and back-off features.
c) LTE-LAA must also adhere to all those deployment rules and requirements considered for using 5GHz unlicensed bandwidth.
d) The sensitivity of coexistence performance is highly dependent to the channel occupancy factors such as collision probability, back-off algorithm, CW update and HARQ feedback. Due to the scheduling latency of LTE the HARQ feedback associated with sub-frame is arrived with 4 ms delay. Hence, the CW window is updated with delay and it causes to increase the number of collisions in the channel.
e) The density of traffic in the channel has an important on the efficiency of coexistence mechanism. When the number of operators' cells and users increase in the channel the LBT coexistence mechanism is found less efficient.
f) In [14] they found LAA inefficient in terms of resource allocation which effect the coexistence performance negatively. They recommended a smart MAC scheduling approach to improve the inefficiency of LAA scheduling.
g) The coexistence performance is not only affected by the behavior of the MAC layer, we also recommend to investigate the aspects of the upper layers such as Radio Link Layer (RLC).
h) In LTE-LAA the collision probability and CW update is based on HARQ feedback, as HARQ feedback is arrived with long delay, we recommend to reduce this delay to its minimum by giving the priority to the associated sub-frame of HARQ feedback.

11. CONCLUSION

We found that the demand for high data rate and stable QoS is one of the serious issues that cellular networks are facing these days. To overcome these issues they require more bandwidth. Operators are unable to respond to these issues by using existing licensed bandwidth. The lack of licensed bandwidth and its high cost made it hard for cellular operators to provide cost effective services to the customers. Cellular operators seriously in need to offload some of their traffic load to get rid of issue of congested networks. 3GPP in R-13 introduced the LTE-LAA a fair solution for offloading of cellular data from licensed bandwidth to the 5GHz unlicensed bandwidth. However, 5GHz band is already in used by Wi-Fi where it will cause coexistence issue between these two technologies. Along this study we studied and understand the channel access mechanisms of LAA and Wi-Fi. Beside this we also presented the coexistence features, problems and challenges, performance differences and performance degradation of each technology. Last but not least, we conducted the simulation results for both Wi-Fi and LTE-LAA. From simulation results we found that the prescribed LBT mechanism by alone cannot bring a fair coexistence between Wi-Fi and LTE-LAA users when they share the same unlicensed operating frequency. Thus, LBT needs more improvement to bring an acceptable fairness.

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