Power Control Based Spatial Reuse for LAA and WiFi Coexistence

Duoduo Hang, Mao Yang(✉), Zhongjiang Yan, and Bo Li

School of Electronics and Information, Northwestern Polytechnical University, Xi'an, China

1714348511@qq.com, {yangmao,zhjyan,libo.npu}@nwpu.edu.cn

Abstract. A rising demand for larger network capacity is leading to the rapid development of the 5th Generation Mobile Communications System (5G). Due to the scarcity of spectrum resources of the conventional licensed band, 3GPP launched the research project of Licensed-Assisted Access using LTE (LAA) in September 2014, aiming to design a single global solution framework and protocol to ensure the efficient operation of LAA on unlicensed band (e.g. 5 GHz spectrum band). However, existing studies indicate that it is difficult to improve the performance of LAA and WiFi at the same time. In this paper, we propose a Power Control based Spacial Reuse scheme (PC-based SR) aiming at increasing the probability of concurrent transmissions in coexisting scenarios of LAA and WiFi. For LAA network, after recognizing existing WiFi signal, it should raise its Energy Detection (ED) threshold and transmit with adjusted power, and vice versa. Our simulation results show that, using the proposed method, the performance of both LAA and WiFi are improved and the fairness to WiFi is enhanced, with respect to throughput and latency.

Keywords: LAA · LBT · Network coexistence · Channel access · Spatial Reuse

1 Introduction

With the rapid increase in the number of mobile users and the diversification of mobile service requirements, a rising demand on network capacity is generated, which promotes the rapid development of the 5th Generation Mobile Communications System (5G). To garantee a better Quality of Service (QoS), it is necessary to increase the licensed spectrum efficiency using new 5G technology. Due to the scarcity of spectrum resources of the conventional licensed band, the unlicensed frequency band has raised public awareness. In comparison to the expensive and crowded licensed band, the unlicensed band has superior in rich spectrum resources, and possess good openness and propagation performance [1]. In September 2014, 3GPP launched the research project of Licensed-Assisted Access using LTE (LAA). The target of LAA is to design a single

© ICST Institute for Computer Sciences, Social Informatics and Telecommunications Engineering 2021
Published by Springer Nature Switzerland AG 2021. All Rights Reserved
Y.-B. Lin and D.-J. Deng (Eds.): SGIoT 2020, LNICST 354, pp. 363–384, 2021.
https://doi.org/10.1007/978-3-030-69514-9_29

global solution framework and protocol to ensure the efficient operation of LAA in unlicensed band. In 2017, 3GPP R16 established the project group for 5G New Radio in Unlicensed Spectrum (5G NR-U), introducing LAA technology into 5G networks.

Although licensing is not compulsory, operations on unlicensed band are still required to obey regional regulations. In addition to various requirements such as indoor-only use, maximum in-band output power, etc., LTE operations in some unlicensed spectrum should also implement Dynamic Frequency Selection (DFS) and Transmit Power Control (TPC) to avoid interfering with radars [2].

Besides, a large number of wireless systems and protocols, such as WiFi, Bluetooth and Zigbee, have already been operating on unlicensed band, among which the most significant one is the WiFi system. Therefore, the deployment of LAA has to consider the fair coexistence with the existing WiFi system. According to 3GPP TR36.889, the impact of an LAA network to WiFi networks shall not be more than that of an additional WiFi network to the existing WiFi services concerning throughput and latency [3].

LTE-U technology is the first version on the market of LTE operating on unlicensed band, proposed by Qualcomm and Ericsson in 2013. Based on Duty-cycle Muting (DCM) scheme, it requires a muting period in LTE for fair coexistence with WiFi. This method is easy for deployment as the conventional LTE frame structure remains the same. But a high probability of collision may still exist at the beginning of each LTE-ON stage.

The present coexistence scheme used in LAA is Listen-before-talk (LBT) scheme, which implements similar function of carrier sensing and backoff procedure as Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) used in WiFi. The basic principle of LBT is to perform transmission(s) after the channel being idle and the backoff counter decremented to zero by Clear Channel Assessment (CCA). The downlink LAA was defined in 3GPP R13, and was extended to the uplink in R14. R.Kwan *et al.* [4] proved by simulation that LBT greatly improves the performance of WiFi in coexisting scenario.

MulteFire is another promising technology for fair coexistence with WiFi. It is a part of 5G NR-U project, requiring LBT scheme, Discrete Transmission (DTX), etc. The major advantage of MulteFire is to operate on unlicensed band independently without a primary carrier on licensed band. The technical detail of MulteFire has not been published yet, LAA is still a hotspot as an important unlicensed LTE technology.

Works have been done aiming to optimize the LBT scheme in LAA system. In [5], a dynamic contention window adaptation method was proposed based on measurement of current buffering length, but the problem of fairness was overooked. In [6–8], the fairness to WiFi is the major concern, yet a trade-off was found inevitable between the two systems.

In this paper, we concern downlink only and propose a Power Control based Spatial Reuse (PC-based SR) scheme for LAA-WiFi coexistence, which increases the probability of concurrent transmissions in coexisting scenarios. An LAA node should raise its Energy Detection (ED) threshold after recognizing WiFi signal and transmit with adjusted power, and vice versa. Simulation results show that, both LAA and WiFi are improved in performance and the fairness to WiFi is enhanced, with respect to throughput and latency.

The rest of this paper is organized as follows. In Sect. 2, we take a deep dive into LAA downlink channel access procedure and give an overview of present studies on LAA-WiFi coexistence. In Sect. 3, we present the MAC protocol and timing analysis of the proposed scheme. Then, we validate performance improvements with simulation results based on NS3 simulator. Finally, in Sect. 5, we conclude the paper and offer a prospect.

2 Related Work

2.1 Downlink Channel Access Procedure for LAA

LAA system uses Cat-4 LBT for transmission(s) including PDSCH (Physical Downlink Shared Channel), PDCCH (Physical Downlink Control Channel) and EPDCCH (Enhanced Physical Downlink Control Channel) [3].

The flowchart of DL LAA channel access procedure with Cat-4 LBT is shown in Fig. 1. An LAA-eNB goes to ICCA (Initial CCA) stage before the first transmission and loops in ECCA(Extended CCA) stage otherwise. During ECCA, LAA transmissions are performed after the channel is sensed to be idle during a defer duration of T_d; and after the counter N is decremented to zero [9]. N stands for the number of slots during which the channel shall be sensed idle; otherwise, an extra defer duration T_d shall be taken for channel sensing.

a) CCA defer duration T_d: $T_d = T_f + m_p \cdot T_{sl}$, where $T_f = 16$us, $T_{sl} = 9$us.
b) Contention Window CW_p: $CW_{min,p} \leq CW_p \leq CW_{max,p}$. The procedure of CW adjustment is as follows [9]:

step 1: for each priority class $p \in \{1, 2, 3, 4\}$, set $CW_p = CW_{min,p}$;

step 2: if more than or equal to 80% of the feedback of HARQ-ACK values in reference subframe k are NACK, increase CW_p to the next higher allowed value and remain in step 2; otherwise, go to step 1.

c) Energy Detection Threshold X_{Thres}: A channel is determined to be idle if the energy detected is less than X_{Thresh}. For coexistence scenarios, the maximum ED threshold is:

$$X_{Thres\_max} = \max \left\{ \begin{matrix} -72 + 10 \cdot log10(\text{BWMHz}/20\,\text{MHz}) \\ \min \left\{ \begin{matrix} T_{max} \\ T_{max} - T_A + (P_H + 10 \cdot log10(\text{BWMHz}/20\,\text{MHz}) - P_{TX}) \end{matrix} \right\} \end{matrix} \right\} \tag{1}$$

where $T_A = 10$ dB (for PDSCH); $P_H = 23$ dBm; P_{TX} is the maximum eNB output power in dBm. $T_{max}(dBm) = 10 \cdot log10(3.16228 \cdot 10^{-8} \cdot BWMHz)$; BWMHz is the single carrier bandwidth in MHz.

d) Maximum channel occupation time $T_{mcot,p}$: An LAA-eNB shall not occupy the channel for more than the duration of $T_{mcot,p}$.
e) Downlink Channel Access Priority Class See Table 1.

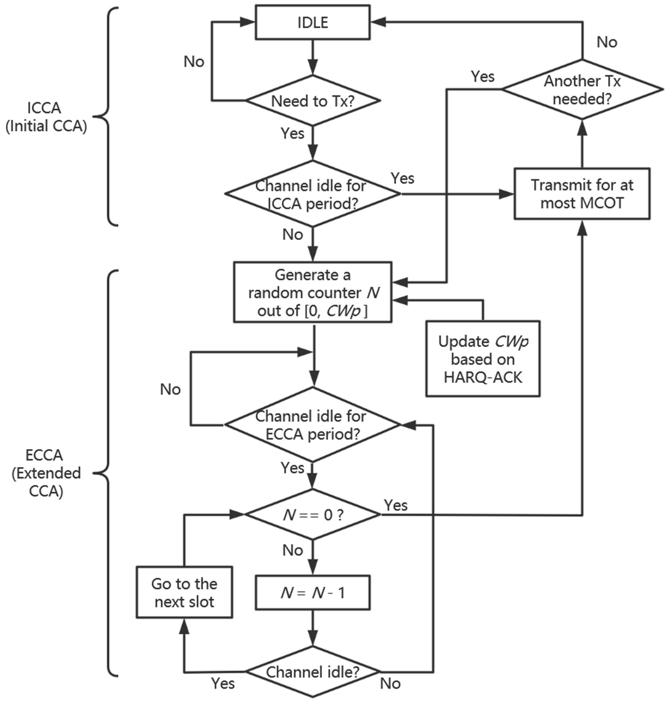


Fig. 1. Flowchart of DL LAA channel access procedure with Cat-4 LBT

Table 1. Downlink channel access priority class

Channel access priority class	m_p	$CW_{min,p}$	$CW_{max,p}$	$T_{mcot,p}$	Allowed CW_p
1	1	3	7	2 ms	{3,7}
2	1	7	15	3 ms	{7,15}
3	3	15	63	8 ms or 10 ms	{15,31,63}
4	7	15	1023	8 ms or 10 ms	{15,31,63,127,255,511,1023}

2.2 Present Studies on LAA-WiFi Coexistence

In terms of performance evaluation, Markov chain is often used to model LAA and WiFi and to analyse the system performance through different KPIs (Key Performance Indicators). The trade-off between channel occupancy time and throughput was analysed in [10]. Success rate of transmission and average throughput with each priority were analysed in [11]. Ref. [12] discussed the conflict probability and channel occupancy rate based on 3GPP R13. Ref. [13] and Ref. [14] set up new frameworks to study the effective capacity and system overhead of LAA respectively. Ref. [15] evaluated the influence of transmit power control and ED threshold. The optimal CW combination of LAA and WiFi was sought in [16], but no corresponding simulation was performed for verification. Ref. [17] compared LBT with DCM, and concluded that the drawback of LBT is the high overhead. Ref. [18] suggested that LAA achieves higher throughput by "suppressing" WiFi as the number of nodes increases.

Researches also conducted abundant of studies on system optimization. In terms of CW adjustment strategies, a CW adaptive adjustment strategy was proposed based on the exchange of QoS information between nodes in [19,20]. However, this method needs the QoS information of each AP (Access Point) and STA (Station), adding extra overheads and complexity. Ref. [6] designed CW adjustment schemes based on air time ratio. In terms of ED threshold, simulation results show that when LAA uses higher detection threshold, the overall network throughput may be improved at the cost of sacrificing WiFi performance [21]. Ref. [22] analysed the influence of ED threshold under imperfect Spectrum Sensing in coexistence scenario. Ref. [23] proposed a distributed algorithm based on downlink collision probability. Another adaptive mechanism based on Unimodal Bandits algorithm was proposed in [24]. Ref. [25] suggested that LAA adopting a higher ED threshold for LAA nodes while a lower one for WiFi nodes improves the fairness to WiFi as well as increases spacial utilization of LAA.

3 Power Control Based Spacial Reuse Scheme

3.1 Basic Idea of Our Proposal

Present studies iindicate the difficulty to improve the performance of both LAA and WiFi at the same time. In this paper, we propose a Power Control based Spacial Reuse scheme (PC-based SR) to increase the probability of concurrent transmissions. We assume that LAA and WiFi networks are able to recognize the signal of each other. A new parameter of Maximum Energy Detection Threshold is added apart from the Normal Energy Detection Threshold.

Take LAA as an example. If an LAA base station recognizes the signal from WiFi node(s) and the energy detected is between the two thresholds, the channel is declared to be idle and transmission(s) shall be performed with a lowered transmit power; otherwise, the transmit power remains the same and the channel state is determined based on the normal energy detection threshold. The power control procedure is same for WiFi.

In this paper, we use ED_{normal} and ED_{max} to represent the normal energy detection threshold and the maximum energy detection threshold respectively; we use $txPower$ and $rxPower$ to represent transmit power and receive power of energy detection in dBm respectively; and P_0 stands for the initial transmit power (not including antenna gain). Figure 2. shows the basic principle of the proposed method. According to Fig. 2, for operator B, when the signal of operator A is detected on a sharing carrier and the energy of which is between ED_{normal} and ED_{max}, it shall lower its transmit power to:

$$txPower = P_0 - (rxPower - ED_{normal}) \tag{2}$$

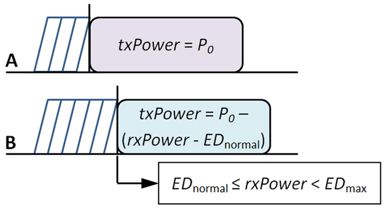


Fig. 2. Basic principle of PC-based SR

and transmit after backoff process, rather than wait until operator A's transmission is finished.

3.2 Protocol Description

The channel access and transmission procedure of LAA/WiFi with PC-based SR in a coexistence scenario is shown in Fig. 3.

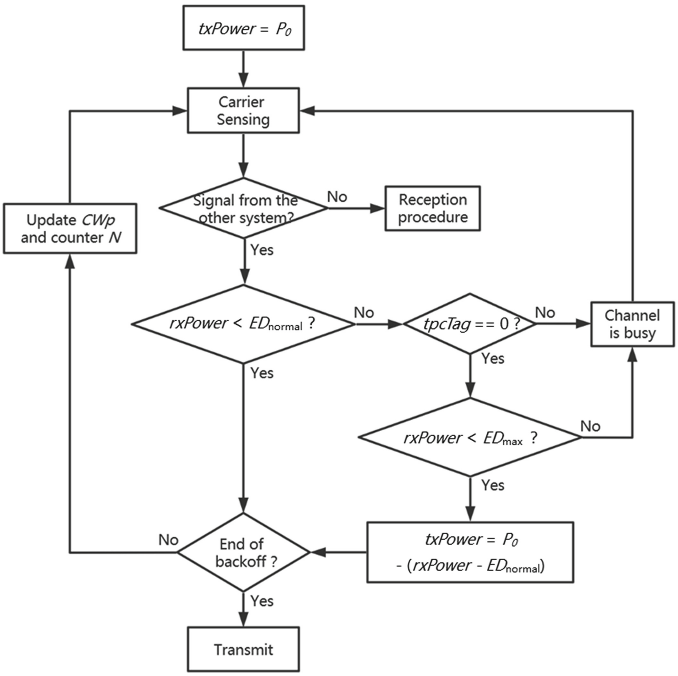


Fig. 3. Channel access and transmission procedure with PC-based SR

In our proposal, a transmit power control tag (i.e., $tcpTag$) is used to avoid the situation that transmissions with lowered power always occur to a certain network. Taking operator B as an example as is shown in Fig. 4. In order to enhance fairness to both systems, a setted *tcpTag* shall be sent along with each packet when using a lowered transmit power, and LAA/WiFi shall compete to access the channel after transmitting with lowered power.

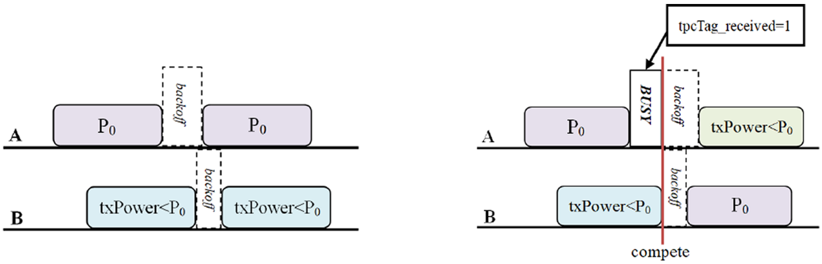


Fig. 4. Transmit without *tcpTag* (left) and with *tcpTag* (right)

LAA and WiFi share a similar transmit power adjustment procedure. Here we take LAA system as an example. If LAA has consecutive packets to transmit with initial *txPower*, during ECCA period,

Step 1: if $rxPower < ED_{normal}$, declare the channel to be idle, and set *tpcTag* to 0 and go to step 4; else, go to step 2;

Step 2: if receives no *tcpTag* from WiFi or the received *tpcTag* equals zero, go to step 3; else, declare the channel to be busy and go to step 1;

Step 3: if $rxPower < ED_{max}$, declare the channel to be busy, and adjust the transmit power to be:

$$txPower = P_0 - (rxPower - ED_{normal}) \tag{3}$$

and set *tpcTag* to be 1, then go to step 4; else, go to step 1;

Step 4: transmit after backoff procedure (if there is one). If another channel access request is required, go to step 5; else go to step 3;

Step 5: reset *txPower* to be P_0, go to step 1.

According to our proposal, for an LAA net device, transmit power adjustment is allowed before transmitting each packet; for an WiFi net device, transmit power adjustment is allowed before transmitting each MPDU. Mention that when using frame aggregation, an A-MPDU of WiFi is carried on one PHY Protocol Data Unit (PPDU), thus all the MPDUs share the same transmit power. To support the proposed scheme, we assume that each PPDU carries one MPDU and several PPDUs transmit consecutively with no or short interframe space. With the development of WiFi-PHY layer, it is expected that MPDUs carried on the same PPDU could use different transmit power in the future.

Algorithm 1. PC-based SR scheme for LAA-WiFi Coexistence

set $txPower \leftarrow P_0$
procedure Channel Sensing
Listening:
  if $rxPower < ED_{normal}$ **then**
    $tcp_{send} \leftarrow 0$
    goto *Idle*
  else
    if $tcpTag_{receive} = 0$ && $rxPower < ED_{max}$ **then**
      $txPower \leftarrow P_0 - (rxPower - ED_{normal})$
      goto *Idle*
    else
      goto *Listening*
    end if
  end if
Idle:
  if $N = 0$ **then**
    transmit
  else
    goto *Listening*
  end if
end procedure

As is recommended by 3GPP and WiFi Alliance, an LAA network shall use a lower energy detection threshold than that of a WiFi network to ensure the fairness to WiFi. When transmitting with initial power P_0, the receive power of energy detection (or channel sensing) can be:

(1) $rxPower \geq ED_{wifi\_max}$
(2) $ED_{laa\_max} \leq rxPower < ED_{wifi\_max}$
(3) $ED_{wifi\_normal} \leq rxPower < ED_{laa\_max}$
(4) $ED_{laa\_normal} \leq rxPower < ED_{wifi\_normal}$
(5) $rxPower < ED_{laa\_normal}$

where ED_{laa_max} and ED_{wifi_max} stand for the maximum energy detection threshold of LAA and WiFi respectively; ED_{laa_normal} and ED_{wifi_normal} stand for the normal energy detection threshold of LAA and WiFi respectively.

We consider the scenario of the coexistence of an LAA cell and a WiFi cell. If an LAA/WiFi base station sends one packet with same size each time after accessing the channel, and if LAA accesses the channel first, Fig. 6, 7, 8, 9 and Fig. 10 present the sequence diagrams by using different color blocks as in Fig. 5.

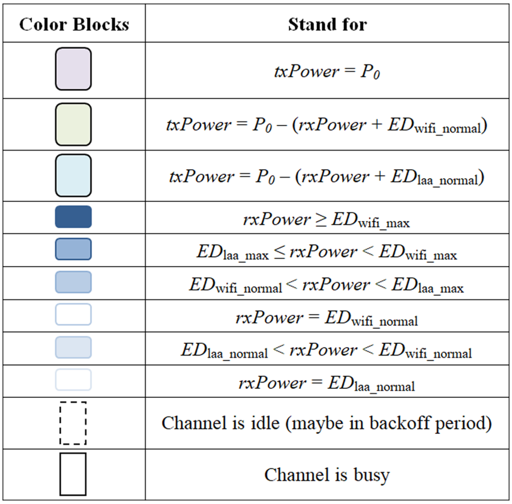


Fig. 5. Legend

Case I. $\boldsymbol{rxPower \geq ED_{wifi\_max}}$
In this case, the base stations of LAA and WiFi are very closed to each other. Therefore, when LAA is sending packets with P_0, the $rePower$ of WiFi is beyond ED_{wifi_max} and the channel is determined to be busy, vice versa. See Fig. 6.

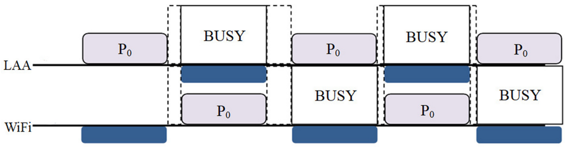


Fig. 6. Case I: $rxPower \geq ED_{wifi\_max}$

Case II. $\boldsymbol{ED_{laa\_max} \leq rxPower < ED_{wifi\_max}}$
Then, we increase the distance between the two cells. In this case, if LAA is transmitting with P_0, the $rxPower$ of WiFi is between its two thresholds and a concurrent transmission with lowered transmit power may be performed. However, if WiFi is transmitting with P_0, the $rxPower$ of LAA is beyond ED_{laa_max} because LAA has lower ED thresholds. See Fig. 7.

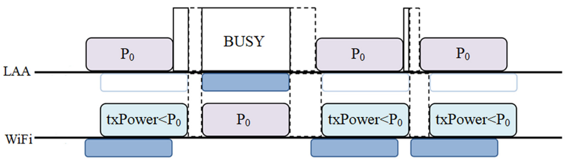


Fig. 7. Case II: $ED_{laa\_max} \leq rxPower < ED_{wifi\_max}$

Case III. $\boldsymbol{ED_{wifi\_normal} \leq rxPower < ED_{laa\_max}}$

Keep on increasing the distance between the two cells. We come to the case where no matter an LAA node or a WiFi node is transmitting with P_0, the energy detected by the other node is between whose two thresholds. Using the proposed method, concurrent transmissions are performed on the shared carrier in the scenario where only one operator used to be allowed to transmit based on traditional configuration. See Fig. 8.

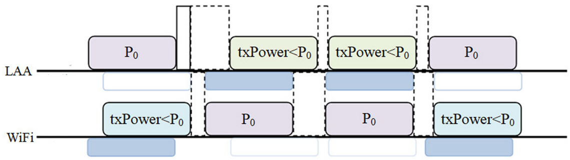


Fig. 8. Case III:$ED_{wifi\_normal} \leq rxPower < ED_{laa\_max}$

Case IV. $\boldsymbol{ED_{laa\_normal} \leq rxPower < ED_{wifi\_normal}}$

In case IV, when LAA is transmitting with P_0, the $rxPower$ of WiFi is below ED_{wifi_normal}, the channel is determined to be idle and the initial transmit power shall be used for transmission. If WiFi is transmitting with P_0, the $rxPower$ of LAA is beyond ED_{laa_normal} but below ED_{laa_max}, thus LAA shall declare the channel to be idle and transmit with lowered $txPower$. See Fig. 9.

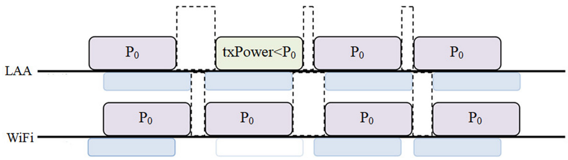


Fig. 9. Case IV:$ED_{laa\_normal} \leq rxPower < ED_{wifi\_normal}$

Case V. $\boldsymbol{rxPower < ED_{laa\_normal}}$

In this case, the LAA cell and the WiFi cell are independent to each other, where the existence of the other network's transmissions cannot be detected based on $ED_{laa_{n}ormal}$ or $ED_{wifi_{n}ormal}$. See Fig. 10.

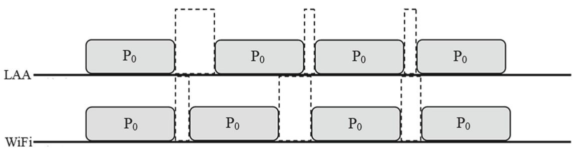


Fig. 10. Case V:$rxPower < ED_{laa\_normal}$

In conclusion, from case II to IV, the probability of concurrent transmissions is increased and the system is expected be improved based on timing analysis.

4 Performance Evaluation

4.1 Simulation Platform

In this paper, we use NS3 Simulator for performance evaluation of the proposed scheme. NS3 is an open source project written in C++ and run primarily on GUN/Linux (such as CentOs, Ubantu, Fedora, etc.) [20]. It is similar to a program library in which a variety of Application Programming interfaces (APIs) are provided for simulating different networks. After downloading and compiling the source code, users can simulate by writing scripts and running scripts (Fig. 11).

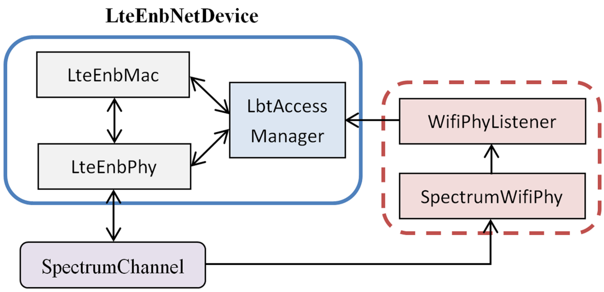


Fig. 11. Structure of LAA

According to the LAA-WiFi-Coexistence platform, elements from WifiNetDevice modeling the lower layer (PHY and lower MAC) are attached to the same SpectrumChannel as a modified LTE device, the main function of which is for carrier sensing and energy detection. A ChannelAccessManager is also added in LteEnbNetDevice. For LBT-based LAA, LbtAccessManager is used for achieving LBT procedures as a subclass of ChannelAccessManager.

4.2 Simulation Scenarios

The basic scenario used in this paper consists of an LAA cell and a WiFi cell (see Fig. 12). Table 2 and Table 3 show the scenario configurations and ED thresholds.

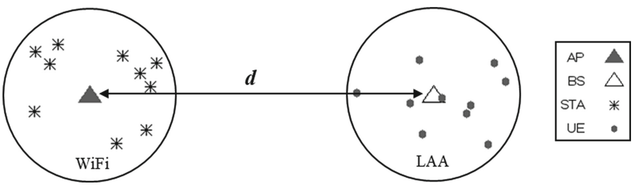


Fig. 12. Basic scenario

Table 2. LAA-WiFi coexistence scenario

Scenario and application layer configuration	Number of cells of LAA/WiFi	1
	Size of each cell (radius)	10 m
	Distance between BSs (d)	Changable/25 m/30 m
	Protocol of application layer	UDP
	Application layer rate	1.2 Mbps/changable
	Size of packet	1000 Bytes
	Transmission mode	Full-buffer transmission (continuous transmission)
LAA parameters	Version	3 GPP R13
	PHY layer Rate	9.9 Mbps
	Rate control algorithm	Constant Rate
	LBT priority class	3
	Mode of radio bearers	UM
	Mode of scheduling	PFS (Proportional Fairness Scheduling)
WiFi parameters	Version	IEEE802.11n
	PHY layer rate	9.9 Mbps
	Rate control algorithm	Constant rate
	Traffic mode	BE (Best Effort)
	Use RTS/CTS or not	Yes
	Maximum size of A-MPDU	65535 Bytes

Table 3. Energy detection threshold for LAA/WiFi with different configurations

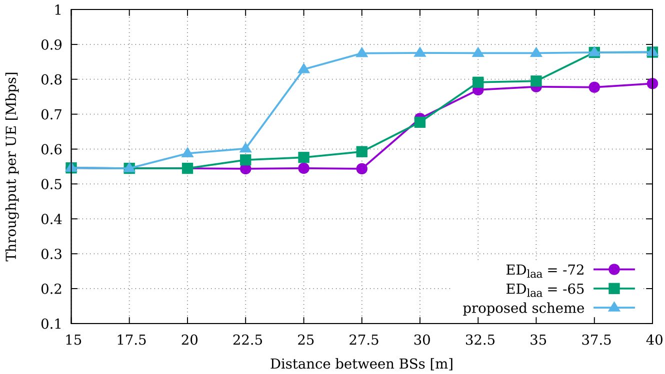
	ED Threshold of LAA	ED Threshold of WiFi
Configuration 1	–72 dBm	–62 dBm
Configuration 2	–65 dBm	–62 dBm
Configuration 3 (proposed scheme)	$ED_{laa\_normal} = -65$ dBm $ED_{laa\_max} = -60$ dBm	$ED_{wifi\_normal} = -62$ dBm $ED_{wifi\_max} = -57$ dBm

(1) **Scenario 1:** $d = 15$ m-40 m, 10 UEs per cell;
(2) **Scenario 2:** $d = 25$ m, firstly change the number of UEs per cell; then change the *udpRate* with 10 UEs per cell;
(3) **Scenario 3:** $d = 30$ m, firstly change the number of UEs per cell; then change the *udpRate* with 10 UEs per cell;

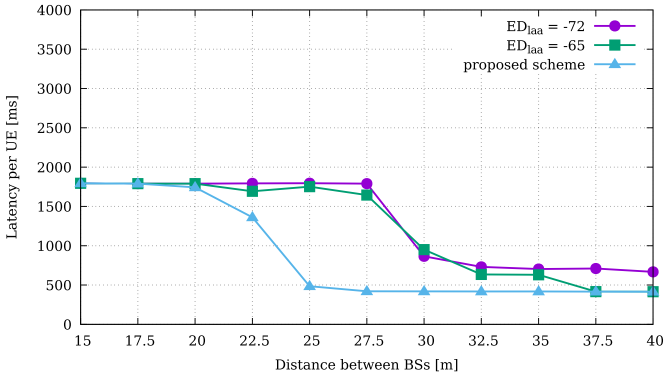
4.3 Simulation Results

In this subsection, we show the simulation results based on NS3 and in scenarios mentioned before.

Scenario 1: performance comparison with different distances between BSs
With the distance d = 20 m− 35 m, there is an overall system performance improvement in terms of throughput and latency when using our proposed scheme of PC-based SR; and with d = 25 m− 30 m, the improvement is the most significant, as is shown in Fig. 13.



(a)



(b)

Fig. 13. Average latency per UE of the overall system with different distances between BSs ($udpRate = 1.2$ Mbps, $ED_{wifi} = -62$ dBm).

We also analyse the performance of LAA and WiFi in the same scenario separately as is shown in Fig. 14. It can be seen that both systems achieve performance improvements using the proposed scheme. For WiFi, the performance improvement is more significant when the distance between BSs is

$d = 25$ m$-30m$, while for LAA, the improvement is more significant when $d = 27.5$ m-35 m.

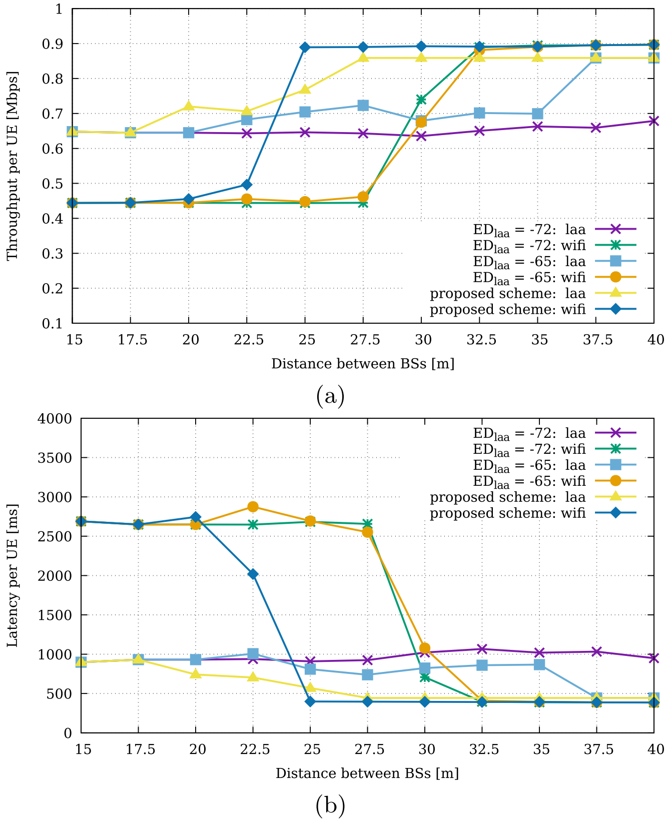


Fig. 14. Average saturation throughput (a) and latency (b) per UE of LAA and WiFi with different distances between BSs ($udpRate = 1.2$ Mbps, $ED_{wifi} = -62$ dBm).

Scenario 2: system performance with $d = 25m$

In this case, if WiFi is sending packets with $txPower = P_0$, the $rxPower$ of LAA is between ED_{laa_normal} and ED_{laa_max}, vice versa. That is, the present scenario is corresponding to *case 3* mentioned in Sect. 3.

The number of UEs per cell indicates the level of traffic in a cell. With a certain amount of the total resources, the more UEs in a cell, the less resources can be allocated to each UE, indicating the higher density of the cell and leading to a lower average saturation throughput of each UE.

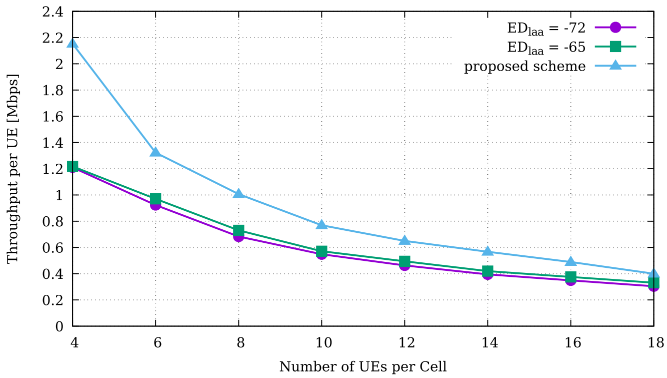


Fig. 15. Average saturation throughput per UE of the ovrall system (d = 25m, $ED_{wifi} = -62$dBm).

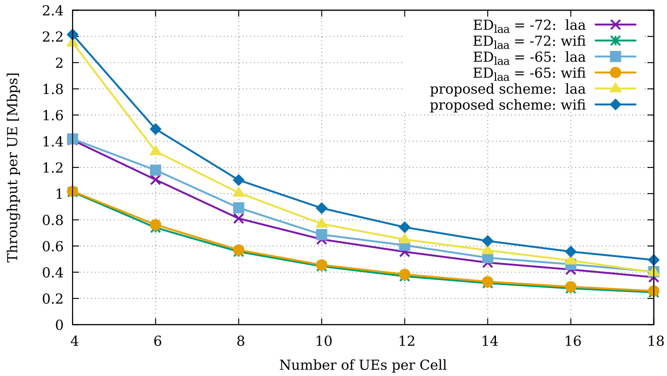
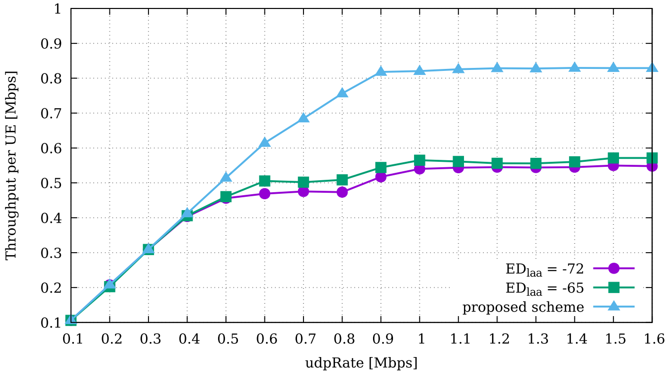


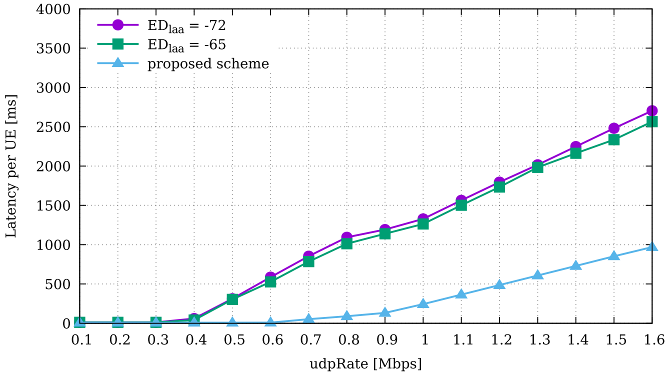
Fig. 16. Average saturation throughput per UE of LAA and WiFi (d = 25m, $ED_{wifi} = -62$dBm).

As can be seen from Fig. 15 and Fig. 16, this method can increase the saturation throughput of LAA and WiFi in both low-density scenarios (e.g., 4 UEs per cell) and high-density scenarios (e.g., 18 UEs per cell). The improvement can be even more significant for cells with fewer UEs. When the number of UEs is 4 for each cell, the average saturation throughput is increased by about 83.3%.

With 10 UEs in each cell, compared to the traditional configuration where $ED_{laa} = -72$dBm and $ED_{wifi} = -62$dBm, using a higher ED threshold for LAA (i.e., $ED_{laa} = -65$dBm) brings a slight increase in overall system performance, while using the proposed scheme increases the performance greatly by about 53.7% of saturation throughput (see Fig. 17).



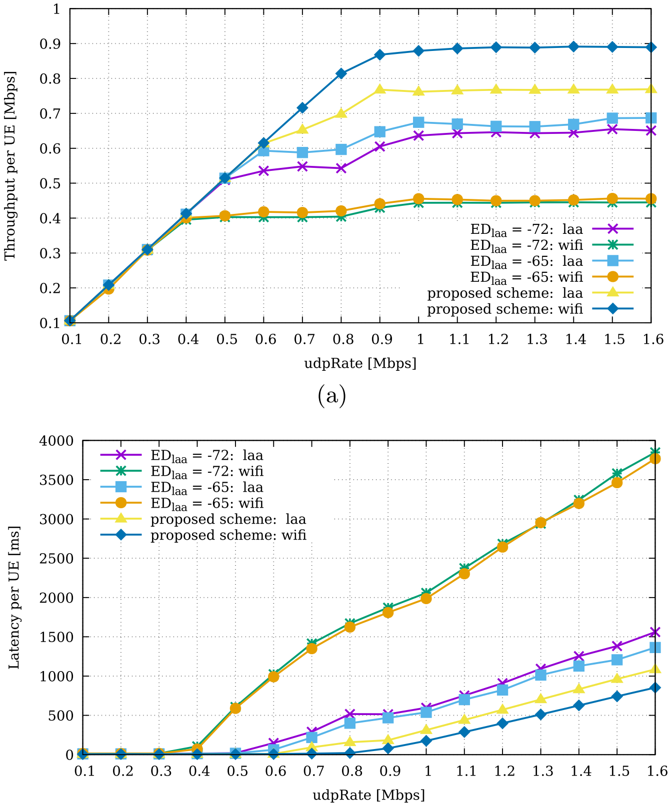
(a)



(b)

Fig. 17. Average throughput (a) and latency (b) per UE of the overall system (d = 25m, $ED_{wifi} = -62$dBm).

In view of performance comparison between LAA system and WiFi system, Fig. 18 shows that both LAA and WiFi are improved in throughput and latency, the saturation throughputs of which grow by 20.3% and 102.3% respectively, enhancing the fairness to WiFi. Table 4 lists the average saturation throughput per UE of LAA cell, WiFi cell and on average.



(a)

(b)

Fig. 18. Average throughput (a) and latency (b) per UE of LAA and WiFi ($d = 25$m, $ED_{wifi} = -62$dBm).

Table 4. Average saturation throughput per UE ($d = 25m$)

	LAA	WiFi	On average
Using traditioanl configuration/Mbps	0.64	0.44	0.54
Using PC-based SR/Mbps	0.77	0.89	0.83
Increased by	20.3%	102.3%	53.7%

Scenario 3: performance comparison with $d = 30m$
In this case, if WiFi is sending packets with $txPower = P_0$, the $rxPower$ of LAA is between ED_{laa_normal} and ED_{laa_max}; if LAA is sending packets with $txPower = P_0$, the $rxPower$ of WiFi is below ED_{laa_normal}. That is, the present scenario is corresponding to *case 4* mentioned in Sect. 3.

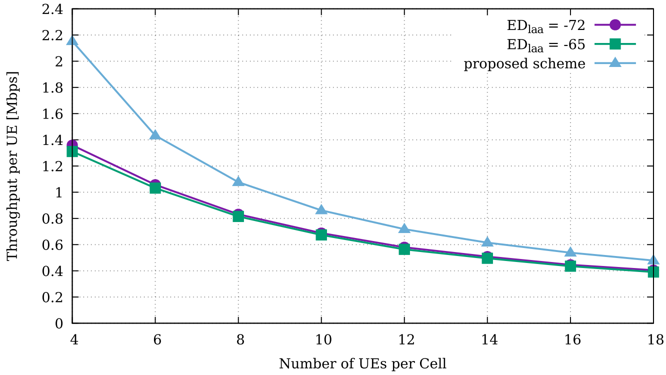


Fig. 19. Average Saturation Throughput per UE of the ovrall system (d = 30m, $ED_{wifi} = -62$dBm).

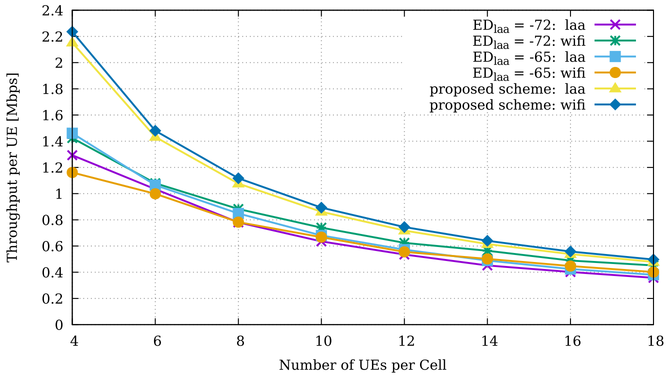


Fig. 20. Average Saturation Throughput per UE of LAA and WiFi (d = 30m, $ED_{wifi} = -62$dBm).

As can be seen from Fig. 19, this method can increase the saturation throughput of LAA and WiFi in both low-density scenarios (e.g., 4 UEs per cell) and high-density scenarios (e.g., 18 UEs per cell). The improvement can be even more significant for cells with fewer UEs. When the number of UEs is 4 for each cell, the average saturation throughput is increased by about 57.1% (Fig. 20).

When each cell has 10 UEs, compared to the traditional configuration where $ED_{laa} = -72dBm$ and $ED_{wifi} = -62dBm$, using a higher ED threshold for LAA(i.e., $ED_{laa} = -65dBm$) increases the overall system performance slightly, while using the proposed scheme increases the performance greatly by about 27.5% of saturation throughput (see Fig. 21).

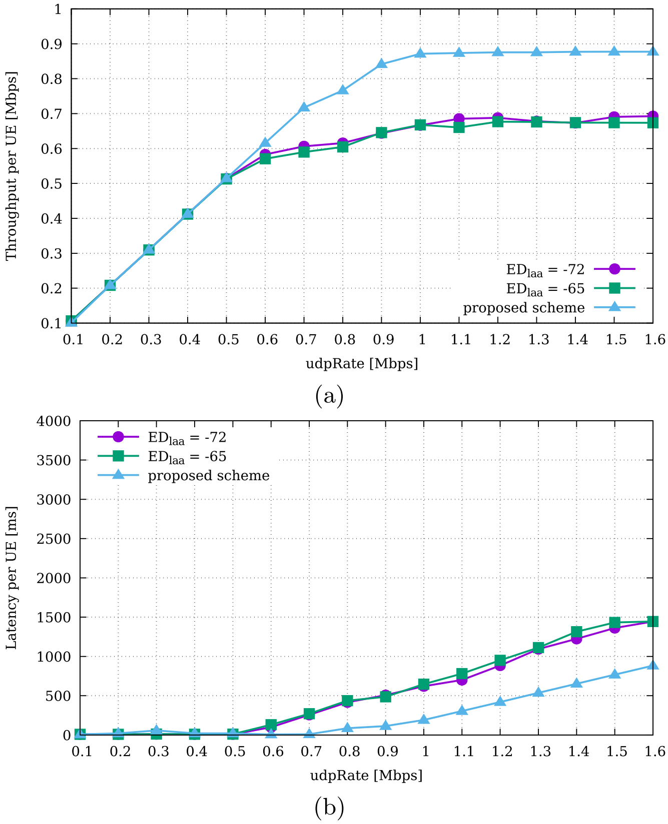
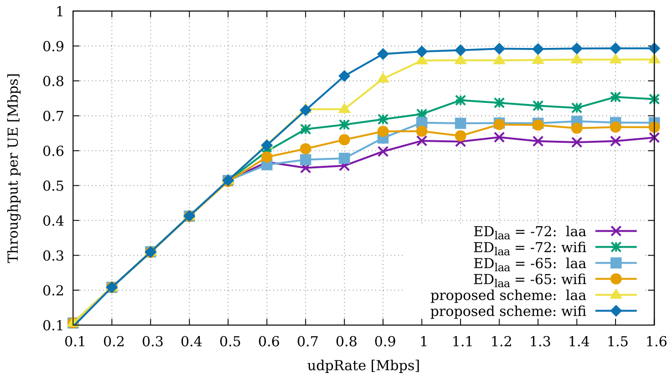
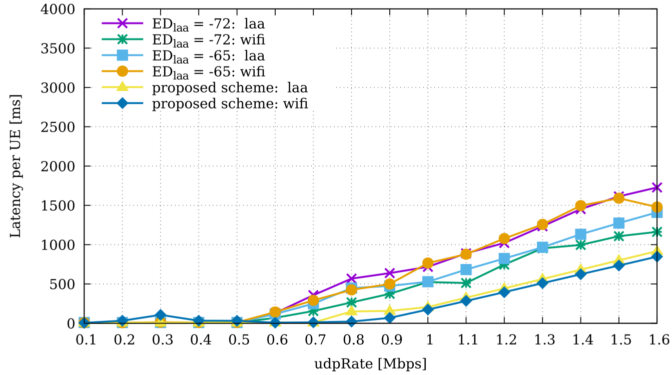


Fig. 21. Average throughput (a) and latency (b) per UE of the overall system ($d =$ 30m, $ED_{wifi} = -62$dBm).

In view of performance comparison of LAA and WiFi, Fig. 22 shows that both LAA and WiFi are improved in throughput and latency, the saturation throughputs of which grow by 36.5% and 20.3% respectively. Table 5 lists the average saturation throughput per UE of LAA cell, WiFi cell and on average.



(a)



(b)

Fig. 22. Average throughput (a) and latency (b) per UE of LAA and WiFi ($d = 30$m, $ED_{wifi} = -62$dBm).

Table 5. Average saturation throughput per UE comparison ($d = 30m$)

	LAA	WiFi	On average
Using traditioanl configuration/Mbps	0.63	0.74	0.69
Using PC-based SR/Mbps	0.86	0.89	0.88
Increased by	36.5%	20.3%	27.5%

5 Conclusions and Future Works

In conclusion, simulation results prove the enhancement of system performance and fairness of our proposal, regardless of traffic density. Specifically, when the distance between the two BSs is $d = 25$m and $d = 30$m, the saturation throughput of overall system is increased by 53.7% and 27.5% respectively; both LAA and WiFi achieve performance improvement in throughput and latency. Future works can be done in LAA uplink access, interaction between cells, hidden node problems between systems, etc.

Acknowledgement. This work was supported in part by Science and Technology on Avionics Integration Laboratory and the Aeronautical Science Foundation of China (Grant No. 20185553035), the National Natural Science Foundations of CHINA (Grant No. 61871322, No. 61771392, No. 61771390, and No. 61501373), and Science and Technology on Avionics Integration Laboratory and the Aeronautical Science Foundation of China (Grant No. 201955053002).

References

1. Zhou, K., Qin, Z., Li, A., Sun, J.: Overview on coexistence technologies of unlicensed band LTE and WiFi. Coll. Commun. Eng. Army Eng. Univ. PLA. **52**(6), 1289–1298 (2019)
2. Kwon, H.J., et al. Licensed-assisted access to unlicensed spectrum in LTE release 13. In: IEEE Communications Magazine, pp. 201–207 (2017)
3. 3GPP TR 36.889. 3rd Generation Partnership Project; Study on Licensed-Assisted Access to Unlicensed Spectrum; (Release 13). Sophia Antipolis Valbonne, France (2015)
4. Kwan, R., et al.: Fair co-existence of Licensed Assisted Access LTE (LAA-LTE) and WiFi in unlicensed spectrum. In: 2015 7th Computer Science and Electronic Engineering Conference (CEEC), pp. 13–18. Colchester (2015)
5. Yan, X., Tian, H., Qin, C., Paul, A.: Constrained stochastic game in licensed-assisted access for dynamic contention window adaptation. IEEE Commun. Lett. **22**(6), 1232–1235 (2018)
6. Wang, W., Xu, P., Zhang, Y., Chu, H.: Network-sensitive adaptive LAA LBT strategy for downlink LAA-WiFi coexistence. In: 2017 9th International Conference on Wireless Communications and Signal Processing (WCSP), pp. 1–6. Nanjing (2017)
7. Alhulayil, M., López-Benítez, M.: Contention window method for improved LTE-LAA/Wi-Fi coexistence in unlicensed bands. In: 2019 International Conference on Wireless Networks and Mobile Communications (WINCOM), pp. 1–6, Fez, Morocco (2019)
8. Alhulayil, M., López-Benítez, M.: Dynamic contention window methods for improved coexistence between LTE and Wi-Fi in unlicensed bands. In: 2019 IEEE Wireless Communications and Networking Conference Workshop (WCNCW), pp. 1–6, Marrakech, Morocco (2019)
9. 3GPP TS 36.213. 3rd Generation Partnership Project; Physical layer procedures (Release 14). Sophia Antipolis Valbonne, France (2016)
10. Tuladhar, S., Cao, L., Viswanathan, R.: Throughput and channel occupancy time fairness trade-off for downlink LAA-Cat4 and WiFi coexistence based on Markov chain (poster). In: 2018 IEEE Conference on Cognitive and Computational Aspects of Situation Management (CogSIMA), pp. 129–134, Boston, MA (2018)
11. Ma, Y.: Analysis of channel access priority classes in LTE-LAA spectrum sharing system. In: 2018 27th International Conference on Computer Communication and Networks (ICCCN), pp. 1–7. Hangzhou (2018)
12. Pei, E., Jiang, J.: Performance analysis of licensed-assisted access to unlicensed spectrum in LTE release 13. IEEE Trans. Veh. Technol. **68**(2), 1446–1458 (2019)

13. Cui, Q., Gu, Y., Ni, W., Liu, R.P.: Effective capacity of licensed-assisted access in unlicensed spectrum for 5G: from theory to application. IEEE J. Sel. Areas Commun. **35**(8), 1754–1767 (2017)
14. Yi, J., Sun, W., Park, S., Choi, S.: Performance analysis of LTE-LAA network. IEEE Commun. Lett. **22**(6), 1236–1239 (2018)
15. Xia, P., Teng, Z., Wu, J.: Transmit power control and clear channel assessment in LAA networks. In: 2015 European Conference on Networks and Communications (EuCNC), pp. 210–213. Paris (2015)
16. Song, Y., Sung, K.W., Han, Y.: Coexistence of Wi-Fi and cellular with listen-before-talk in unlicensed spectrum. IEEE Commun. Lett. **20**(1), 161–164 (2016)
17. Cano, C., Leith, D.J.: Unlicensed LTE/WiFi coexistence: is LBT inherently fairer than CSAT?. In: Proc. IEEE International Conference on Communications (ICC), pp. 1–6 (2016)
18. Bitar, N., Al Kalaa, M.O., Seidman, S.J., Refai, H.H.: On the coexistence of LTE-LAA in the unlicensed band: modeling and performance analysis. In: IEEE Access, vol. 6, pp. 52668–52681 (2018)
19. Tao, T., Han, F., Liu, Y.: Enhanced LBT algorithm for LTE-LAA in unlicensed band. In: 2015 IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), pp. 1907–1911. Hong Kong (2015)
20. Hao, F., Yongyu, C., Li, H., Zhang, J., Quan, W.: Contention window size adaptation algorithm for LAA-LTE in unlicensed band. In: 2016 International Symposium on Wireless Communication Systems (ISWCS), pp. 476–480. Poznan (2016)
21. Dama, S., Kumar, A., Kuchi, K. Performance evaluation of LAA-LBT based LTE and WLAN's co-existence in unlicensed spectrum. In: 2015 IEEE Globecom Workshops (GC Wkshps), pp. 1–6, San Diego, CA (2015)
22. Pei, E., Lu, X., Deng, B., Pei, J., Zhang, Z.: The impact of imperfect spectrum sensing on the performance of LTE licensed assisted access scheme. IEEE Trans. Commun. **68**(3), 1966–1978 (2020)
23. Li, L., Seymour, J.P., Cimini, L.J., Shen, C.: Coexistence of Wi-Fi and LAA networks with adaptive energy detection. IEEE Trans. Veh. Technol. **66**(11), 10384–10393 (2017)
24. Gao, X., Qi, H., Wen, X., Zheng, W., Lu, Z., Hu, Z.: Energy detection adjustment for fair coexistence of Wi-Fi and LAA: a unimodal bandit approach. In: 2019 IEEE 5th International Conference on Computer and Communications (ICCC), pp. 1086–1091. Chengdu, China (2019)
25. Hong, S., Lee, H., Kim, H., Yang, H.J.: Lightweight Wi-Fi frame detection for licensed assisted access LTE. IEEE Access **7**, 77618–77628 (2019)