Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

Proportional Fairness for Long-Term Evolution-Licensed Assisted Access (LTE-LAA) with Wi-Fi Coexistence in Unlicensed Spectrum

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ARTICLE INFO

Article history:
Received 23 June 2023
Received in revised form 28 October 2023
Accepted 3 November 2023
Available online 4 March 2024

Keywords:

LTE; Licensed Assisted Access (LAA); Wi-Fi; Integration; Unbiased proportional; Unlicensed spectrum

ABSTRACT

Long-Term Evaluation-Licensed Assisted Access (LTE-LAA) has good potential for fair coexistence with Wi-Fi in an unlicensed spectrum. Though the LTE-LAA utilizes the same listen before-talk technique as the distributed coordination function in IEEE 802.11, it utilizes completely different parameters and transmission durations. For this reason, a fair coexistence between LTE-LAA and Wi-Fi leaves an open question on how the LTE-LAA network should choose its parameters. To tackle this issue, an analytical framework considering the effects of varying important parameters, which are the different initial back-off window sizes, the numbers of sensing durations, the maximum back-off stages, the number of retransmissions and the transmission opportunities for LTE-LAA and Wi-Fi nodes on their performances has been developed. The node and network airtime performances are evaluated by using the current standard parameters setting to see how this setting affects the node and network airtime performances. From there, optimal settings of the initial backoff window size and number of sensing durations are applied by using the obtained node airtime equation that is derived from the Markov renewal process and evaluated as functions of system parameters. The optimum initial backoff window size and number of sensing durations of LTE-LAA are evaluated and verified by the calculation and simulation using MATLAB software. The analysis shows that LTE-LAA maintained unfair coexistence with Wi-Fi by using the current standard parameter setting as its initial back off window size or sensing duration. But in contrast, using the optimum initial backoff window size and number of sensing durations of LTE-LAA shows that they can maintain proportional fairness. It is unconcealed that the initial backoff window size tuning of LTE-LAA carries a high possibility of achieving fairness because it needs less system data and achieves a higher exactness result.

1. Introduction

Research on the integration of LTE-LAA and Wi-Fi networks rapidly increases, and the focus grows on finding ways to tackle the issues regarding fairness when the networks coexist. A few years ago,

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https://doi.org/10.37934/araset.41.1.7689

this was not a big issue since there were limited uses of networks, but the technologies have grown as the years keep adding up.

There are many communicating devices invented, such as smartphones, tablets, laptops and other portable or non-portable devices that can let those communications happen. These developments create cruciality in adapting a huge wireless connectivity especially for the Internet of things (IoT) and cyber physical systems (CPSs). Many connected nodes are required to communicate with one another and connect to the network that applies specific quality of service (QoS).

The 3rd Generation Partnership Project (3GPP) provides solutions for this issue, but it is still an open question on how to efficiently increase fairness between networks. Wi-Fi networks are built from the inception for sharing among the in-network nodes through the carrier sense multiple access collision avoidance (CSMA/CA) which is a distributed random access collision avoidance. But LTE was designed for great capability licensed operation based on a centralized scheduler that allocates network resources among in-network nodes. So, as the new specifications needed to attain sharing by LTE, Wi-Fi’s mechanism naturally extends to the spectrum to do the same. This is happened because LTE was designed to not share with a non-LTE system.

Creating a fair integration of these two networks is not an easy task and leads to challenges such as optimizing the energy detection threshold of LTE-LAA, adjusting the contention window size, and many other parameters to be analyzed. The goal is to make these two networks integration fair to each other in any acceptable sense. The values for those parameters must be studied to determine whether they require higher or lower values. In the 3GPP definition, it is said that LAA design should aim for a fair coexistence with Wi-Fi networks to not have more impact on Wi-Fi services than additional Wi-Fi networks on the same carrier with respect to throughput and latency [1]. There are a few obvious circumstances that need to be sought and recognized to harmonize the rights of these networks as they integrate with each other. Numerous research works have studied the analytical models to achieve network integration and provided necessary additions assumption, such as the collision time in LTE-Wi-Fi is identical to that in pure Wi-Fi networks, but this is obviously not an accurate assumption as the time length of the collisions will be different. There is also the assumption that the initial back-off window size and maximum back-off stage for both networks are identical, but they are not in practice.

The escalating demand for the cellular networks’ throughput resulted in the 3GPP consortium establishing the LTE-LAA technology. But the major problem encountered is the biased performance of LTE-LAA in coexistence with Wi-Fi networks. Regarding that issue, LTE-LAA then presents the listen-before-talk (LBT) channel access mechanism for equal channel coexistence. Many studies are done by comparing the channel access methods used in Wi-Fi and LTE-LAA and evaluating the performance of the LBT modifications [2]. Previous studies [2] proposed a few scenarios considering the different configurations of LTE-LAA and Wi-Fi networks, but the issue is that in the result achieved, the throughput gain was slightly unfair for Wi-Fi and LTE-LAA shown in both options in the scenarios.

Nevertheless, from paper [1], assuming an infinite number of retransmissions and identical transmission slots for all the nodes cannot be openly practiced in the LTE-Wi-Fi coexisting case; thus, the goal was to create an analytical model for LTE-LAA and Wi-Fi coexistence. The research sheds light on a critical new solution for LTE-LAA fair coexistence. The two tuning parameters for LTE-LAA examined were the initial backoff window size tuning and sensing duration tuning, respectively. To achieve fair coexistence, the initial backoff window size of LTE-LAA should be in linear proportion to Wi-Fi, and the proportionality should be controlled by the ratio of holding times in successful transmission of LTE-LAA nodes and Wi-Fi nodes. As an alternative, if the sensing duration was altered, the optimal number of sensing durations of LTE-LAA was further dependent on the number of LTE-LAA and Wi-Fi nodes and the backoff parameters, including the initial backoff window size, the maximum backoff stage, and the maximum number of retransmissions. The node airtime and total network airtime of LTE-Wi-Fi coexisting networks were proven by simulation based on the proposed model in paper [1].

Each Wi-Fi node should pay attention to the channel before transmission to check the channel's availability, referring to the Distributed Coordination Function (DCF) for sharing access to the channel based on the CSMA/CA scheme [3]. It uses different parameters and a variety of transmission durations, which leaves many possibilities. For this reason, a pragmatic framework discusses the method of LTE-LAA in selecting its parameters. For instance, before transmission, to check the channel availability, Wi-Fi node should listen to the channel, and if it is idle, the transmission will proceed. The research paper [3] also discussed how the LBT algorithm found that the parameters play important roles are the Contention Window (CW) and the Clear Channel Assessment (CCA). So, the static CW method was introduced but although it achieved improved throughputs for the existing Wi-Fi network, the fairness condition in terms of throughput was not entirely met for all traffic loads.

This paper [4] describes the design of the LTEPro network, which combines LTE-LAA and LTELWA. By designing an appropriate distance, density as a ratio, and bandwidth allocation between three technologies to find the best cell location for high throughput. Furthermore, an adaptive power control for cochannel femtocells is presented in this paper [5]. To avoid co-channel interference, femtocells must detect the presence of macro users in their surroundings. The author proposed an effective approach called the Adaptive Smart Power Control Algorithm (ASPCA) in the paper [6]. Next, the authors [7] explore the user throughput and spatial spectral efficiency (SSE) of multi-UC coexisting LTE-LAA and Wi-Fi networks versus network density using the Matern hard core process in this paper.

Due to this lacking way of assuming, the interest in research works regarding this issue is growing, yet it remains unexplored [8-25]. In this research, the methodology in previous research [1] that focuses on the tuning parameters, which are the initial backoff window size and sensing duration, will be analyzed to bring out the analytical framework. Different sensing durations and initial backoff window sizes will be selected and varied, as well as other values in the setting for the analysis to achieve better precision. So, this study focuses on the coexistence scenario of LTE-LAA nodes, $n^{(L)}$ and Wi-Fi nodes, $n^{(W)}$. Same type node of Ψ have identical backoff parameters including the initial backoff window size, $CW^{(\Psi)}$, the number of sensing slot/duration, $A^{(\Psi)}$, the maximum backoff stage, $K^{(\Psi)}$ and the retry limit, $M^{(\Psi)}$. (Ψ = L, W). When accessing channel, the LTE-LAA nodes transmit for a continuous duration of TXOP $T^{(L)}$μs. The Wi-Fi nodes transmit a data packet of $PL^{(W)}$ bits with a transmission bit rate $R^{(W)}$Mbps for the same purpose. Following that, this research highlights tuning approaches for two of LTE-LAA parameters, which are the initial backoff window size and sensing duration tuning. These two parameters are being evaluated with the proposed optimal tuning by following the 3GPP recommendation so that LTE-LAA and Wi-Fi can maintain proportional fairness by maintaining their parallel node airtime, regardless of the network size, which is variable. The remainder of this research is organized as follows: Section 2 explains the methodology performed for this study, which is verified by the simulation results and discussion in Section 3. Finally, concluding remarks are summarized in Section 4.

2. Methodology

2.1 Flowchart

An understanding regarding the parameter approaches, which are the initial backoff window size tuning and the sensing duration tuning, is gained, and they are said to be in linear proportion for both LTE-LAA and Wi-Fi node transmission. From this parameter, an analytical framework will be analyzed with optimal tuning where LTE-LAA and Wi-Fi can always maintain identical node airtime, regardless of variation in network size. This analytical framework will capture key features such as different initial backoff window sizes, numbers of sensing slots, maximum backoff stages, retry limits, and transmission opportunities for LTE-LAA and Wi-Fi nodes. Next, the node airtime in integration will be evaluated as a function of the number and the backoff parameters of LTE-LAA and Wi-Fi nodes. Not only that, but the effects will also be analyzed. The analysis will be simulated in MATLAB software to show relationship between the ratio of the node airtime of a Wi-Fi node and a LTE node, the ratio of their holding times in successful transmission, the ratio of their initial backoff window sizes and the difference of their numbers of sensing slots. After all the procedures are done, it is a crucial step to analyze the node airtime performances, the backoff parameters and the effects of the key parameters to make sure all the goals have been achieved. If the results do not come out as desired, the procedures will be repeated and the adjustments for the key parameter values will be amended. The flowchart for this project is illustrated in Figure 1 below.

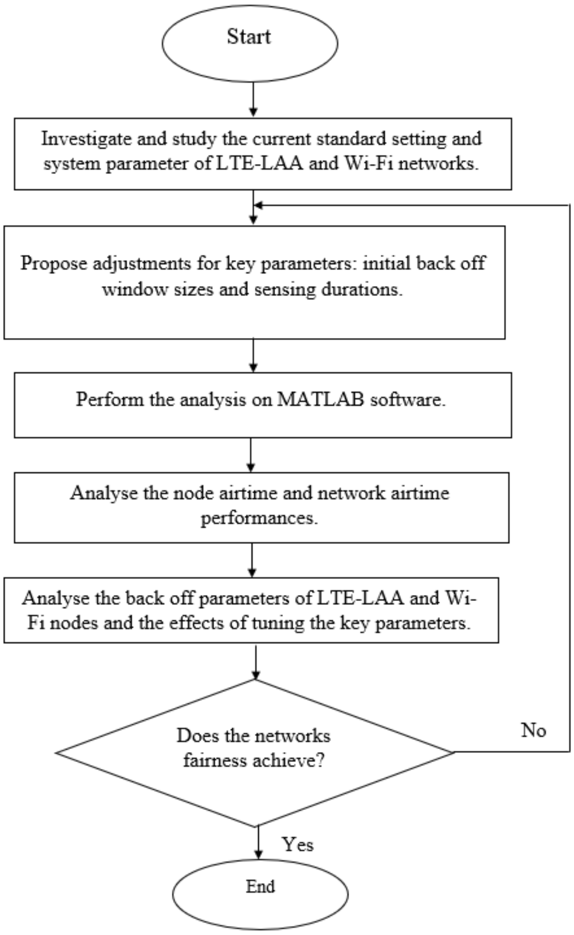


Fig. 1. Flowchart

2.2 Current Standard Setting and System Parameters

The assumption describing a modeling assumption and its limitations, as well as potential ways to improve the accuracy of the model made in a recent work that models IEEE 802.11e EDCA networks is adapted. The assumption is that the backoff process in the network is homogeneous, even when nodes have different sensing durations. This assumption was also made in the previous work cited (reference [21]), and it was found to be a good approximation in the case where nodes have different initial backoff window sizes. However, if nodes have a significant difference in sensing durations, this assumption may cause a deviation.

It is also noted that the accuracy of the assumption can be improved when the initial backoff window sizes of nodes are large enough. In other words, if nodes have larger backoff window sizes, the deviation caused by differences in sensing durations may be less significant, and the assumption of a homogeneous backoff process may be a better approximation.

Medium Access Control (MAC) protocols of Wi-Fi and LTE-LAA taking relevance measures and reasons regarding network performance analysis and its consequent impact on the proportional integration or coexistence. In the first part of this section, this research will discuss about the random-access structures of LTE-LAA LBT and the system parameters used for the analytical model of LTE-Wi-Fi integration networks. The key structures of LTE-LAA LBT used are as below:

i. Access Priority: defines the different access priority classes which are divided into four. These classes are different for their distinct traffic types.
ii. Transmission Duration: when a node wins channel access, it is permitted to transmit a TXOP duration up to 10 ms, or 8 ms in coexistence mode.
iii. Channel Sensing Duration: LTE-LAA node depending on their access priority class must show a Clear Channel Access (CCA) check using “energy detect” mechanism over a defer period of T_f = 16 µs followed by several time slots with slot length of 9 µs.
iv. Backoff Parameters: LTE-LAA with different access priority have different backoff parameters as tabulated in Table 1. Besides following the IEEE 802.11 standard networks, the backoff parameters of each Wi-Fi node are fixed as also written in Table 1.

Table 1
Current standard setting in LTE-LAA and Wi-Fi [21]

	A	CW	K	M
LTE-LAA Class 1	16 + 1 x 9 *µs*	4	1	2 *ms*
LTE-LAA Class 2	16 + 1 x 9 *µs*	8	1	2 *ms*
LTE-LAA Class 3	16 + 3 x 9 *µs*	16	2	8 or 10 *ms*
LTE-LAA Class 4	16 + 7 x 9 *µs*	16	4	8 or 10 *ms*
Wi-Fi	16 + 2 x 9 *µs*	16	6	Payload-dependent

The multi-group analysis in this research can be general, as both LTE-LAA and Wi-Fi have respective different priority classes when considering each access priority class of nodes.

A model for analyzing channel contention among nodes in coexisting networks of Long-Term Evolution-License Assisted Access (LTE-LAA) and Wi-Fi. The model can be represented as a multi-queue, single-server system, which means that multiple queues of data packets are competing for service from a single server (the wireless channel). The service time distribution, which is the time it takes for a packet to be transmitted over the channel, is determined by the state of head-of-line (HOL) packets. In other words, the packets at the head of each queue will receive service first, and the time it takes to transmit them will determine the service time distribution.

The model is based on an analytical framework proposed in a previous work cited as a reference [21], which analyzed a similar network, namely a multi-class IEEE 802.11e EDCA network. The model in this passage extends this framework to the LTE-LAA and Wi-Fi coexisting networks, which have different characteristics and challenges.

Overall, the research paper [21] describes a model that represents the network as a queuing system, with multiple queues of packets competing for access to a single channel. The model is based on a previous analytical framework and has been extended to the LTE-LAA and Wi-Fi coexisting networks. All the equations and mathematically designed models refer to previous works in [1,21].

The interval between successive transitions is called the holding time. For Wi-Fi node's successful transmission, its holding time with the basic access mechanism can be written as Eq. (1).

$$\tau_T{}^{(W)} = \frac{1}{\sigma}\left(\frac{PL^{(W)}}{R^{(W)}} + OH\right) \tag{1}$$

σ denotes as the length of the time slot and *OH* denoted the overhead including the PHY header, ACK frames that are transmitted with a fixed basic rate RB and few interframe spaces which can be written as Eq. (2).

$$OH = \frac{ACK}{R_B} + PHY\ header + DIFS + SIFS \tag{2}$$

For LTE-LAA node, it will occupy the channel for TXOP of $T^{(L)}$ once it successfully accessed. The holding time in successful transmission of the LTE-LAA node can be written as Eq. (3).

$$\tau_T{}^{(L)} = \frac{T^{(L)} + D_{LTE}}{\sigma} \tag{3}$$

D_{LTE} is the next transmission delay which is 500 µs represents one LTE slot as an LTE-LAA node will not transmit until the beginning of the next LTE slot. Meanwhile the holding time in collision of Wi-Fi node and LTE-LAA node can be written as Eq. (4) and Eq. (5).

$$\tau_F{}^{(W)} = \frac{1}{\sigma}\left(\frac{PL^{(W)}}{R^{(W)}} + PHY\ header + DIFS\right) \tag{4}$$

$$\tau_F{}^{(L)} = \frac{T^{(L)} + D_{LTE}}{\sigma} \tag{5}$$

Two types of nodes as in the model that is contend for the channel with LBT-based MAC scheme is considered using varying backoff parameters and transmission durations.

Table 2 summarized the values of system parameters of LTE-LAA, and Wi-Fi used in the simulations. Based on Table 2, according to Eq. (1) and Eq. (4), the holding time $\tau_T{}^{(W)}$ in the successful transmission state and $\tau_F{}^{(W)}$ in collision states for the Wi-Fi nodes can be calculated as $\tau_T{}^{(W)}$= 315.5 time slots and $\tau_F{}^{(W)}$= 309.4 time slots. Other details assumptions in the system model are no decoding errors, infinite buffer, and no hidden terminals. Considering all the conditions and assumptions, the discussion on the tuning of the initial backoff window size and sensing duration of LTE-LAA is done.

Table 2
System parameter setting of Wi-Fi and LTE-LAA [1]

Parameter	Value
PHY Header	20 µs
ACK	112 bits + PHYH
DIFS	34 µs
SIFS	16 µs
Slot Time σ	9 µs
Basic Rate R_B	6 Mbps
Packet Payload Length $PL^{(W)}$	2^{16} bits
Data Rate $R^{(W)}$	24 Mbps
Initial Backoff Window Size of Wi-Fi $CW^{(W)}$	16
Number of Sensing slots of Wi-Fi $A^{(W)}$	2
Maximum Backoff Stage of Wi-Fi $K^{(W)}$	6
Retry Limit of Wi-Fi $M^{(W)}$	1
Maximum Backoff Stage of LTE-LAA $K^{(L)}$	6
Retry Limit of LTE-LAA $M^{(L)}$	1

2.3 Airtime Performances

There are two airtime performances that is discussed in this study which is the node airtime for each of the LTE-LAA and Wi-Fi node and the other one is the network airtime. The node airtime is the fraction of channel time used for successful packet transmissions. The node airtime for LTE-LAA node is denoted as $\lambda_{out}^{(W)}$ and the node airtime for Wi-Fi node is denoted as $\lambda_{out}^{(L)}$. The network airtime, $\hat{\lambda}_{out}$ is the sum of node airtime of LTE-LAA nodes and Wi-Fi nodes. The ratio of node airtime of a Wi-Fi node and an LTE-LAA node can be written as Eq. (6).

$$\frac{\lambda_{out}^{(W)}}{\lambda_{out}^{(L)}} = \frac{\tau_T^{(W)}}{\tau_T^{(L)}} \cdot \frac{CW^{(L)}}{CW^{(W)}} \cdot p_A^{A^{(W)}-A^{(L)}} \cdot \frac{1-(1-p_A)^{K^{(W)}+M^{(W)}}}{1-(1-p_A)^{K^{(L)}+M^{(L)}}}$$

$$\cdot \frac{\frac{1}{2p_{A-1}}+(\frac{1}{p_A}-\frac{1}{2p_{A-1}}-\frac{(1-p_A{}^{M^{(L)}}}{p_A})(2-2p_A)^{K^{(L)}}}{\frac{1}{2p_{A-1}}+(\frac{1}{p_A}-\frac{1}{2p_{A-1}}-\frac{(1-p_A{}^{M^{(W)}}}{p_A})(2-2p_A)^{K^{(W)}}} \tag{6}$$

Since the unbiased proportional of the LTE-LAA and Wi-Fi nodes is achieved when node airtime is identical or equal, the equation can be written as Eq. (7).

$$\lambda_{out}^{(W)} = \lambda_{out}^{(L)} \tag{7}$$

By combining Eq. (6) and Eq. (7), by tuning the initial backoff window sizes, the numbers of sensing slots, maximum backoff stages or the maximum number of retransmissions, it shows clearly that the proportional fairness can be achieved. But, in this study, only the framework for the tuning of the first two parameters which are the initial backoff window sizes, and the numbers of sensing slots are being analyzed and are assumed that both networks node has same maximum backoff stages and maximum number of retransmissions.

For the initial backoff window size tuning, the time when the network operates in contention mode, the optimal backoff window size is focused as on this research, it can be stated that the backoff window size cannot be too small or too high because it will cause collisions and delays. Hence, the optimal initial backoff window size is studied.

Assuming that the number of sensing slots for both Wi-Fi and LTE nodes are equal, the optimal initial backoff window size, $CW_{PF}^{(L)}$ of LTE-LAA can be obtained as below by combining Eq. (1), Eq. (3), Eq. (6) and Eq. (7) as shown in Eq. (8).

$$CW_{PF}^{(L)} = \frac{\tau_T^{(W)}}{\tau_T^{(L)}} \cdot CW^{(W)} = \frac{T^{(L)}+D_{LTE}}{\frac{PL^{(W)}}{R^{(W)}}+OH} \cdot CW^{(W)} \tag{8}$$

From Eq. (8), $CW_{PF}^{(L)}$ is linear to Wi-Fi node initial backoff window size, $CW^{(W)}$ and the proportionality factor depends on $\frac{\tau_T^{(W)}}{\tau_T^{(L)}}$, the ratio of holding times for successful transmission. For this reason, the longer the TXOP of LTE-LAA node $T^{(L)}$, the bigger initial backoff window size should be to get unbiased integration with Wi-Fi. The sensing duration is fixed to 2 and the value of TXOP is fixed to 8 ms. The value of $CW_{PF}^{(L)}$ is calculated from Eq. (8) and it gives the value of 48.

The optimal number of sensing slots of the LTE nodes is derived by considering that both Wi-Fi and LTE nodes have an equal initial backoff window size, i.e., $CW^{(W)}$= $CW^{(L)}$, and be written as Eq. (9).

$$A_{PF}^{(L)} = A^{(W)} - \frac{ln\,(\frac{\tau_T^{(W)}}{\tau_T^{(L)}})}{ln\,p_A} = A^{(W)} - \frac{ln(\frac{T^{(L)}+D_{LTE}}{\frac{PL^{(W)}}{R^{(W)}}+OH})}{ln\,p_A} \tag{9}$$

by combining Eq. (1), Eq. (3), and Eq. (6), the difference between $A_{PF}^{(L)}$ and the number of sensing slots of Wi-Fi nodes $A^{(W)}$ is not determined by holding time during successful transmission, but the network steady-state point, p_A as well.

3. Results and Discussion

3.1 Initial Backoff Window Size Tuning

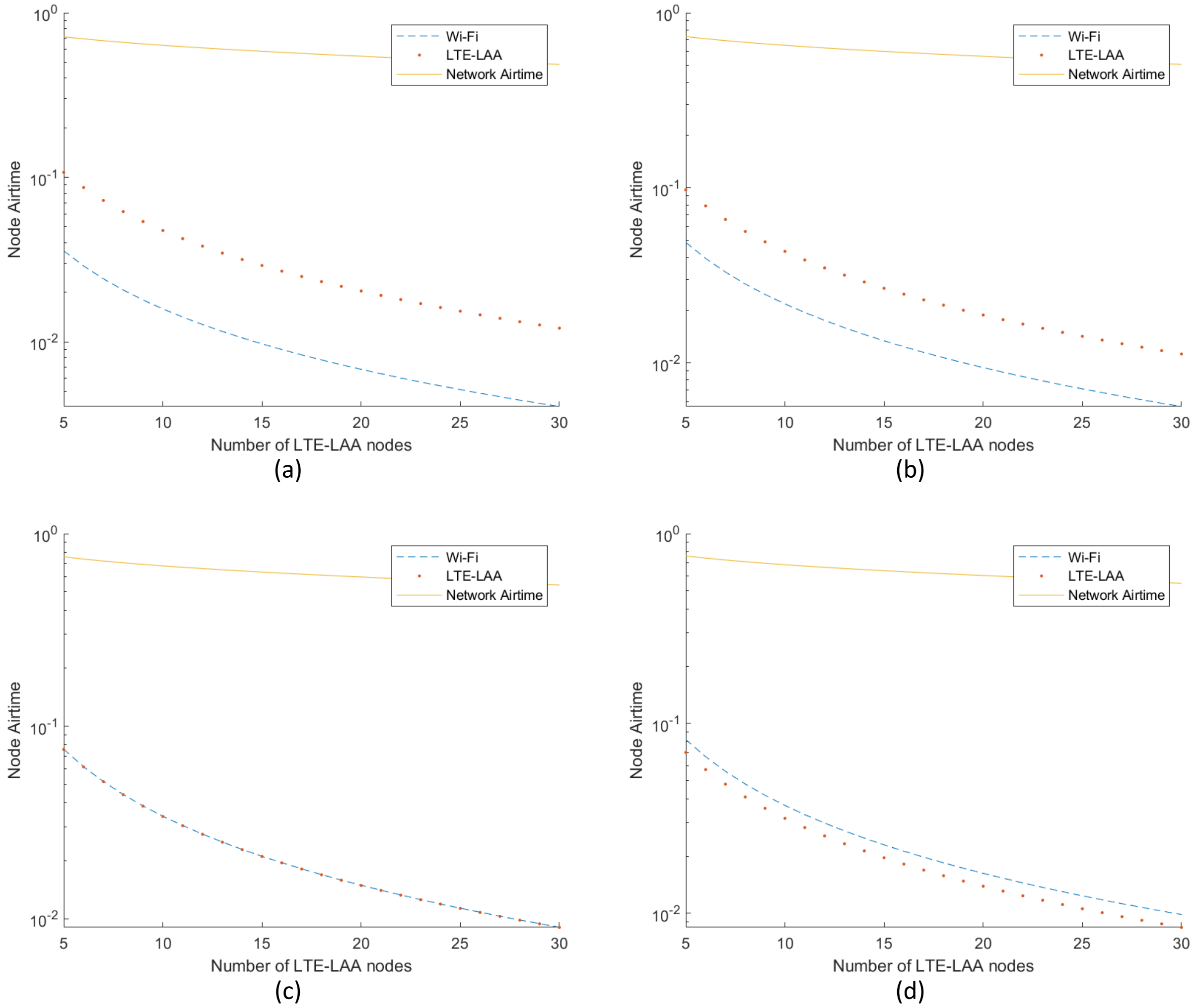
For the initial backoff window size tuning, the optimal backoff window size is focused as on this research, it can be stated that the backoff window size cannot be too small or too high because it will cause collisions and delays. So, optimal value of it will be the ideal ones. Assuming that the number of sensing slots are the same, $A^{(W)}= A^{(L)}$. The values from the calculation taken from section 2.2 is used for the simulation to see the performance of the node airtime for both network nodes and the network airtime.

Table 3 shows the values used in the MATLAB simulation to study the outcomes of the airtime performances for both LTE-LAA and Wi-Fi nodes. The initial backoff window size ranged from 16 to 80. The highlighted value, which is 48 in the table, is the optimal backoff window size for LTE-LAA nodes. The sensing duration is fixed to 2, and the value of TXOP is fixed to 8 ms.

Table 3
Initial backoff window size tuning

$CW^{(W)}$	$CW^{(L)}$
16	16
16	24
16	32
16	40
16	48
16	56
16	64
16	72
16	80

Figure 2 shows the results obtained from simulations made with different values of the initial backoff window size of LTE-LAA nodes. The values used are as stated in Table 3. From Figure 2(a) and Figure 2(b), the node airtime performances for LTE-LAA are higher than those for Wi-Fi, while in Figure 2(d), the node airtime performance is vice versa because Wi-Fi node airtime performances are higher than those for LTE-LAA. But not in Figure 2(c), when 48 is used as the initial backoff window size of LTE-LAA nodes. The performance for both nodes is nearly the same and have higher total network airtime. This condition proved that the best value of the initial backoff window size is 48, which is the optimal backoff window size. It can be said that unbiased proportionality for the integration of LTE-LAA and Wi-Fi networks are achieved when the number of nodes for both networks at the same ratio.



(a) (b) (c) (d)

Fig. 2. The node airtime versus the number of LTE-LAA nodes at (a) $CW^{(W)} = 16$, $CW^{(L)} = 16$. (b) $CW^{(W)} = 16$, $CW^{(L)} = 24$. (c) $CW^{(W)} = 16$, $CW^{(L)} = CW_{PF}^{(L)} = 48$. (d) $CW^{(W)} = 16$, $CW^{(L)} = 56$.

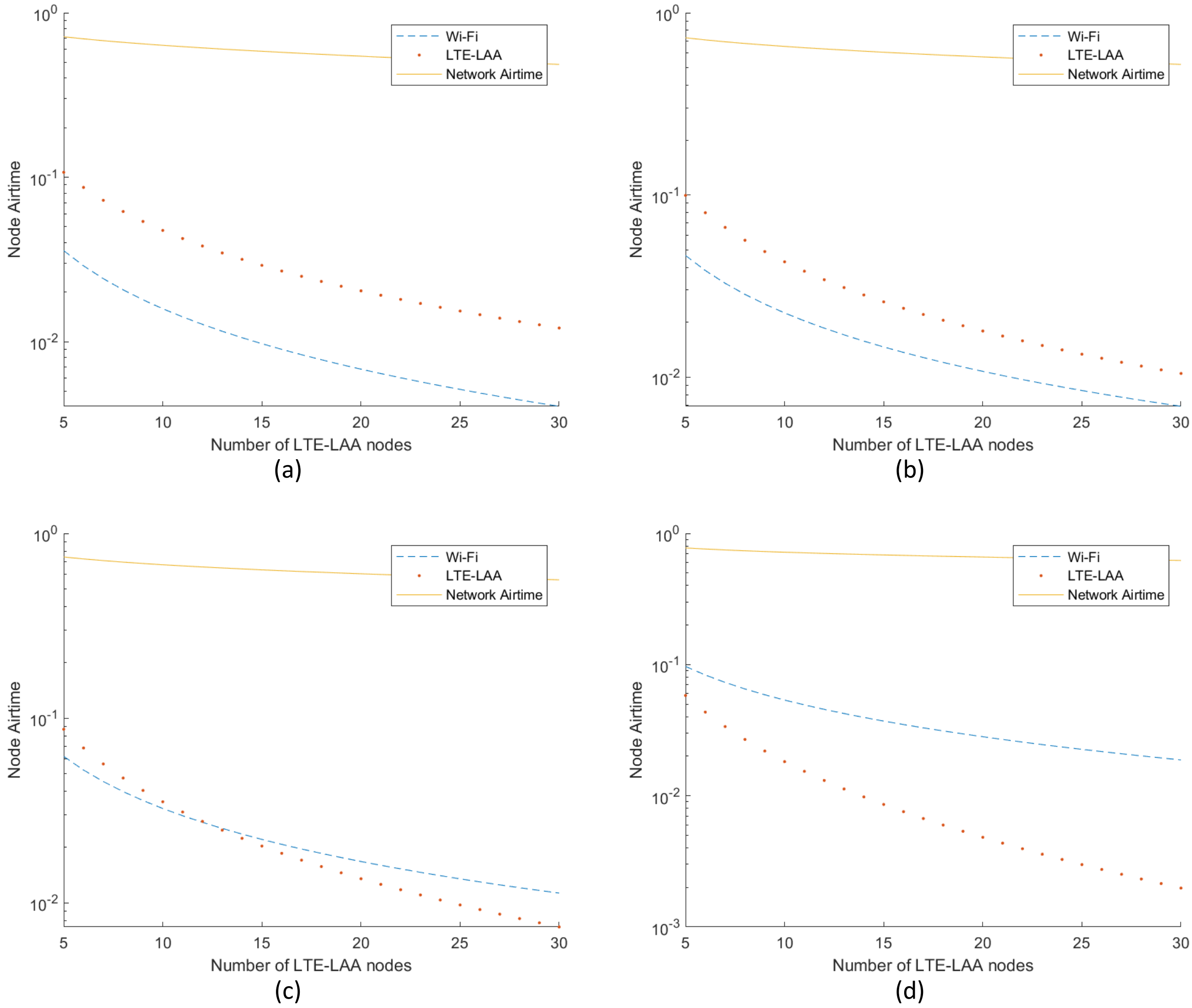
3.2 Sensing Duration Tuning

Table 4 shows the values of the sensing duration that are being varied at the LTE-LAA nodes. The sensing durations of Wi-Fi are fixed to 2. The initial backoff window size for both LTE-LAA and Wi-Fi nodes is fixed at 16.

Table 4
Sensing duration tuning

$A^{(W)}$	$A^{(L)}$
2	2
2	2.7
2	3
2	3.7
2	4
2	4.7
2	5
2	6

Figure 3 further illustrates the airtime performance with $A^{(L)}$= 2 and $A^{(L)} = A_{PF}^{(L)}$, respectively. In contrast to the un-equal airtime with the default/fixed setting as in Figure 3(a), LTE-LAA nodes and Wi-Fi nodes resulting to almost identical node airtime despite the variety of network sizes with the optimal setting, as Figure 3(c) illustrates. By comparing Figure 2(c) and Figure 3(c), the simulated node airtime of LTE-LAA and Wi-Fi nodes slightly deviates from each other with the optimal sensing duration setting being used. There are errors introduced when rounding the optimal number of sensing slots to the nearest integer during calculations. The rounding part of the calculation is also done for the initial backoff window size, but the effect of rounding errors is much more noticeable in the case of tuning the sensing duration as the ratio of node airtimes of two types of nodes is exponential in the difference of the number of sensing slots.



(a) (b) (c) (d)

Fig. 3. The node airtime versus the number of LTE-LAA nodes at (a) $A^{(W)} = 2, A^{(L)} = 2$. (b) $A^{(W)} = 2, A^{(L)} = 2.7$. (c) $A^{(W)} = 2, A^{(L)} = A_{PF}^{(L)} = 3.7$. (d) $A^{(W)} = 2, A^{(L)} = 6$

4. Conclusions

In this research, the fairness issue of the coexistence of LTE-LAA and Wi-Fi networks is analysed with various system parameters, focusing on the initial backoff window size and the sensing duration. A function of system parameters of nodes in each type, based on which the node airtime λ(Ψ)out and the network total airtime $\hat{\lambda}_{out}$ are further analysed with the derivation of the network steady-state operating point p_A in saturated conditions. The analysis shows that the ratio of the node airtime of a Wi-Fi node and a LTE node is inversely proportional to the ratio of their initial backoff window sizes, linear to the ratio of their holding times in successful transmission and exponential to the difference of their numbers of sensing durations. To maintain unbiased proportionality between LTE-LAA and Wi-Fi, the optimal initial backoff window size $CW_{PF}^{(L)}$ and number of sensing slots $A_{PF}^{(L)}$ of LTE-LAA nodes are obtained. Particularly, in achieving the unbiased proportional, the initial backoff window size of LTE-LAA nodes should be linearly increased with Wi-Fi nodes' initial backoff window size, and what determines the increasing rate is the ratio of their holding times in successful transmission, $\frac{\tau_T^{(W)}}{\tau_T^{(L)}}$. Furthermore, by tuning the sensing duration, the optimal number of sensing slots $A_{PF}^{(L)}$ of LTE-LAA and Wi-Fi differences is evaluated by $\log A_{PF}^{(L)}$, which is dependent on the steady-state point p_A. This research discusses the importance of pragmatic network design for the coexistence of LTE and Wi-Fi networks. In other words, the relationship between standard and optimal settings indicates that optimal settings not only allow each LTE and Wi-Fi node to always achieve the same node airtime, but also achieve higher across the network airtime performance. This indicates that LTE-LAA nodes should consider adaptive adjustment of backoff parameters to improve both fairness and overall network performance. Proportional fairness can be achieved by adjusting the initial backoff window size or the number of sensing duration in LTE-LAA nodes, but the analysis reveals that adjusting the initial backoff window size is the preferred option as it needs less system information and gives better feasibility and accuracy. No decoding errors due to noise and no hidden terminals are the important keys of assumption in this research. More accurate-designed models need further establishment to take the effects of decoding errors, hidden terminals and HARQ mechanism into consideration for real-world conditions. For future studies about proportional fairness, the analysis can be further extended to study other quality-of-service (QoS) guarantees, such as delay constraints in LTE-Wi-Fi coexisting networks, which is another interesting issue that deserves more attention. Link adaptation is another interesting topic worthy of future research when discussing how to achieve fairness.

Acknowledgement

This paper is part of research work that supported by MOHE Grant file no.: FRGS/1/2019/TK04/UITM/02/26 and School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA Shah Alam.

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