Performance Evaluation of LTE-LAA and Wifi Coexistence Based on Cat-4 Procedure

[1]Azita Laily Yusof, [2]Farah Nabila Rizal Al-Muhammady, [3]Norsuzila Ya'acob
[1,2,3]School of Electrical Engineering, College Engineering, Universiti Teknologi MARA, Shah Alam, Selangor
[1]laily012001@yahoo.com, [2] farahrizal046@gmail.com, [3]norsuzilayaacob@yahoo.com

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Abstract
In recent years, mobile data traffic has significantly increased and licensed bands have become more scared and congested. This occurs when the demand for digital connectivity has grown exponentially over the years as people today heavily rely on technology. For that reason, to enhance the existing LTE performance, a favorable, economically viable and promising initiative was introduced by implementing LTE in the unused spectrum. Licensed Assisted Access (LAA) for LTE has been proposed by the Third Generation Partnership Project (3GPP) for addressing user needs. Despite employing the Listen-Before-Talk (LBT) method, this proposed network has had issues in integration with other networks, WiFi. This is because of the various factors, including the window backoff size and sensing period length. The integration of LTE-LAA and WiFi networks employing the Category-4 (CAT-4) technique is evaluated in this study. Since it conducts similarly to the CSMA/CA protocol that is applied by end users of WiFi, the CAT-4 procedure is chosen. As a result, MATLAB was used in this study's evaluation to simulate the airtime performance for WiFi and LTE-LAA networks. Based on the findings, it was concluded that the performance of both networks during airtime is mostly influenced by the appropriate values of LTE sensing duration and the window backoff size. Hence, when both parameters are tuned to optimal, the best performance for coexistence between the two networks is guaranteed.
Keywords: fair coexistence, License Assisted Access, LTE, unlicensed spectrum, WiFi

Introduction

The growing use of mobile and smart devices had resulted in higher demand for data bandwidth and volume of traffic. Mobile operators and network providers have looked at various options due to the licensing spectrum limitations and constraints. To lessen the LTE network congestion, unlicensed spectrum technology was investigated by major mobile carrier companies [1]. By bringing LTE into the 5 GHz unlicensed spectrum, the performance of wireless and the optimization of mobile data resources may be significantly improved, as a result, producing the outstanding potential for the prospect of mobile telecommunication [1].

The unlicensed spectrum's sharing nature has made it incredibly challenging to accomplish the fair coexistence of LTE and other heterogeneous networks like WiFi while having a more cost-effective solution and a larger network capacity [15]. The most difficult problem is increasing LTE throughput while preventing significant WiFi system deterioration when both the LTE and the WiFi networks are operating under the same spectrum

[11]. All WiFi APs must first listen before sending to an open channel since WiFi systems use CSMA/CA protocols [11]. Therefore, WiFi networks may be held responsible if they use the same bands as LTE [11]. LTE transmission utilizes channel access along with slotted central scheduling, whereas WiFi technology relies on contention techniques, particularly the CSMA/CA protocol. Therefore, a strategy for a just coexistence arrangement is required to avoid any interference that harms the functioning of both networks [15].

Two main strategies for unlicensed band LTE coexistence are available to coexist harmoniously with WiFi systems. The first approach is LTE-U, which employs duty-cycling methods and the CSAT mechanism in nations like the USA, China, and Korea [5][6]. The LTE-LAA or LTE Licensed Assisted Access, also known as the second known operation, utilizes the Listen-Before-Talk (LBT) method that functions similarly to CSMA/CA. [4]. Since there are regulatory restrictions on using the 5 GHz unlicensed band, LTE-LAA is mostly used in Europe and Japan [2][3]. The 3GPP cooperation created LTE-LAA to utilize the unlicensed spectrum under the 5 GHz frequency.

LTE-LAA unlicensed spectrum coexistence has been carried on in this work since LTE-LAA is suitable for bigger territories and a low density of WiFi base stations is required for the improvement of LTE and WiFi networks, as suggested in [1][21]. LTE-LAA is more practical and lucrative across most countries as it practices the LBT mechanism [15]. Users of LTE-LAA must sense the channel before broadcasting anything to prevent interference with other nodes [15]. Additionally, it was suggested that LTE service can be enhanced by LTE-LAA, particularly in specific corporate environments or hotspots [4]. Furthermore, LTE-LAA has significant advantages over WiFi alone and functions well with WiFi [12]. Even when employing the LBT technique, LTE-LAA still performs poorly when the channels are extremely congested and interfered with heavily [7][13][14]. In this study, the two networks are assessed by employing the CAT-4 procedure to ensure fair coexistence between the two networks.

The remaining sections of the paper are divided into four groups. Section II will discuss in more detail the related research on how LTE-LAA and WiFi cohabit with one another. In Section III, the research methodology performed for this study will be presented. Section IV explains the simulation results and discussion, and lastly, Section V concludes to conclude this paper

Related Works

The LTE-LAA [1]-[20] channel access standard was introduced by the 3GPP, commonly known as the Third Generation Partnership Project, with its main objective to meet the demand for the two networks' service efficiency under the shared spectrum. In earlier publications, numerous strategies and fixes for improved network performance have been put forth. Network operators believe that deploying the LTE Licensed Assisted Access service into the unlicensed frequency band is a potential solution for improving the service of the 4G or 5G wireless networks. To combine the primary LTE licensed band carrier with the secondary 5 GHz unlicensed band carrier, carrier aggregation is essential in the system. Additionally, the LTE-LAA protocol applies the LBT mechanism, which functions similarly to the CSMA/CA protocol. This is being done to avoid and prevent any conflicts or interference with other wireless systems.

The LBT mechanism in LTE-LAA is classified into four types. The LTE CAT-4 protocol is the most popular because it works similarly to the WiFi CSMA/CA protocol. However, CAT-4 from LTE and CSMA/CA may have different backoff processes, slot times and sensing duration. As mentioned in papers [15][19], more research on CAT-4 procedures is still needed, as not many studies are done. Despite the LBT mechanism's capacity to maintain the transmission harmony between LTE and other heterogeneous unlicensed systems, like WiFi, the coexistence of the two networks is far from perfect as collision and interference still occur [1][8][15]. Because WiFi can only send data while the channel is open, the WiFi output efficiency can be degraded by the presence of the LTE-LAA network [15].

According to the authors of [8][9][15], there are two most important LTE-LAA factors to consider. The holding times ratio measured under the successful transmission process of LTE-LAA and WiFi networks should be considered when determining the LTE-LAA initial backoff window size. The ideal LTE-LAA sensing slot count for adjusting sensing duration is further reliant on the combined WiFi and LTE-LAA node count [8]. The node airtime differential is significantly impacted by variations in sensing duration. According to a study [15], the prolonged LTE-LAA transmission times are primarily to blame for the coexistence fairness issues that arise. Moreover, since WiFi uses an exponential backoff window, LTE-window LAA's size is not adaptive when compared to WiFi. A configurable size of the window for the LTE-LAA network is required to improve coexistence performance. The best method for selecting LTE-LAA and WiFi nodes in the most efficient window size is required.

Although other strategies to optimize the performance of the two networks have already been proposed in recent years in some research papers [9]–[18]. As such, the authors of the study [10] stated that by incorporating LTE-LAA and WiFi coexistence with the Monte Carlo approach, also known as "3DMCAT," it was discovered that its throughput performance has been increasing. In addition, the authors of the study [11] suggested that a quality of service (QoS) aware strategy should be employed, with its emphasis being primarily on the QoS metrics, particularly the transmission latency and throughput, for LTE-LAA and WiFi coexistence systems to perform well. In this situation, despite LTE-ability LAA's to improve LTE services by using the spectrum with WiFi, it may still be limited in their ability to guarantee QoS for customers due to acute contention with the existing WiFi system.

According to several recent studies [13–18], the LTE-LAA-based-LBT channel access mechanism is incapable of achieving ideal coexistence between these two systems and requires more significant improvement. Therefore, machine learning (ML) based intelligence has usually been recognized as a way to offer customers a large and affordable bandwidth since it can enhance channel access to unlicensed wireless networks [17]. The authors of this study [15] used machine learning techniques, specifically reinforcement learning (RL) to optimize the window size contention of the two networks. Based on studies [15–18] that combine RL and ML with LTE-LAA and WiFi coexistence, the LTE-LAA and WiFi networks' performance is significantly improved.

To prevent any degradation and collision that can consequently impact the overall performance of the network, it is crucial and essential to have a system for both existing WiFi and LTE-LAA nodes that is fair and harmonious. Figure 1 depicts the system framework for a shared LTE and WiFi networks operating in an unlicensed band [21]. The LTE and WiFi nodes share the same unlicensed band in this scenario, with LTE providing service to LTE user equipment (L-UEs) [11]. The WiFi access point (AP) transmits data to its WiFi user equipment (W-UEs) using the CSMA/CA protocol [8][11].

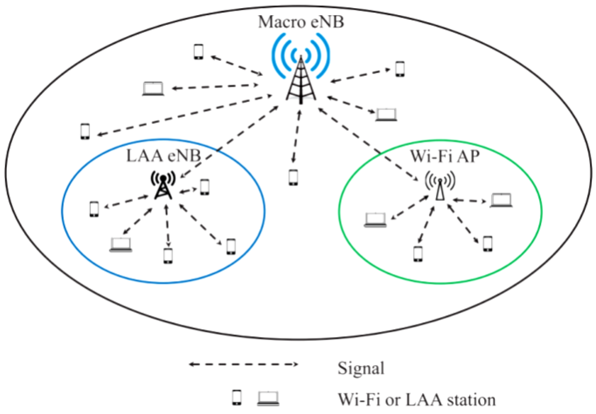

Fig. 1: The graphic illustration for the coexistence scenario for the two networks under one spectrum [21]

Methodology

The primary objective of this study is to assess the two networks employing the CAT-4 procedure to achieve equitable coexistence between the two networks. In this study, calculations are performed to determine the ideal backoff window size, airtime performance, and sensing length. MATLAB is used to do simulations for network airtime performance.

System Parameters

Before conducting the research, parameter settings for the two networks are set and depicted in Table I. The equations that are used in this research are also shown in this section. These equations are then used in MATLAB to tune the initial size of the backoff window, $CW^{(L)}$ and sensing duration $A^{(L)}$ of LTE-LAA. Optimal values of the initial size of the backoff window and sensing duration are also performed.

TABLE I Standard parameter setting for LTE-LAA and WiFi systems [8]

System Parameter	**Value**
ACK	112 bits+PHYH
PHY Header	20 µs
SIFS	16 µs
DIFS	34 µs
Basic Rate RB	6 Mbps
Slot Time σ	9 µs
Data Rate $\mathbf{R}^{(W)}$	24 Mbps
Length of Packet Payload $\mathbf{PL}^{(W)}$	216 bits
WiFi Initial Size of Backoff Window Size $\mathbf{CW}^{(W)}$	16
WiFi Sensing Slots $\mathbf{A}^{(W)}$	2

WiFi Maximum Backoff Stage $\mathbf{K^{(W)}}$	6
LTE-LAA Maximum Backoff Stage $\mathbf{K^{(L)}}$	6
WiFI Retry Limit $\mathbf{M^{(W)}}$	1
LTE-LAA Retry Limit $\mathbf{M^{(L)}}$	1

Airtime Performance

The effectiveness of the two networks was assessed using node airtime calculations for the nodes of both LTE-LAA and WiFi. For more effective transmission of the packet, node airtime, also known as channel time, is required for the system. Node airtime or channel time can be expressed using Equation (1).

$$\lambda_{out}^{(\psi)} = \tau_T^{(\psi)} / \left(\tau_F^{(\psi)} \frac{1-\rho_A}{\rho_A} + \frac{1}{2\alpha \rho_A^{A^{(\psi)}-A_{\min}}} + CW^{(\psi)} \right.$$
$$\cdot \left(\frac{1}{2\rho_A - 1} + \left(\frac{1}{\rho_A} - \frac{1}{2\rho_A - 1} - \frac{(1-\rho_A)^{M^{(\psi)}}}{\rho_A} \right) (2-2\rho_A)^{K^{(\psi)}} \right)$$
$$\left. / \left(2\alpha \cdot \rho_A^{A^{(\psi)}-A_{\min}} \cdot \left(1 - (1-\rho_A)^{K^{(\psi)}+M^{(\psi)}} \right) \right) \right)$$

(1)

The symbol ψ can be assumed as W or L for node for the two networks. $\lambda_{out}^{(\Psi)}$ is the node airtime, whereas the holding time when successful transmission occurs, ρ_A is the point of steady state. Furthermore, $CW^{(\Psi)}$ is the contention window that will be presented in the next section. This equation for the airtime performance can be also simplified to a simpler version;

$$\lambda_{out}^{(\psi)} \approx \frac{2\alpha \tau_T^{(\psi)} \rho_A^{A^{(\psi)}+A_{\min}} \left(1 - (1-\rho_A)^{K^{(\psi)}+M^{(\psi)}} \right)}{CW^{(\psi)} \left(\frac{1}{2\rho_A - 1} + \left(\frac{1}{\rho_A} - \frac{1}{2\rho_A - 1} - \frac{(1-\rho_A)^{M^{(\psi)}}}{\rho_A} \right) (2-2\rho_A)^{K^{(\psi)}} \right)} \quad (2)$$

Where $\lambda_{out}^{(\Psi)}$ is the node airtime, $\tau_T^{(\Psi)}$ is the successful transmission holding time, ρ_A is the steady-state point. $CW^{(\Psi)}$ is the contention or backoff window size. From equation (1), the value for the initial size of the backoff window of both LTE-LAA $CW^{(L)}$ and WiFi system $CW^{(W)}$ can be tuned and adjusted. As for the network performance, it is the sum of LTE-LAA airtime node $\lambda_{out}^{L)}$ and node airtime of WiFi $\lambda_{out}^{(W)}$.

The Size of Optimal Backoff Window

Backoff window scheme or also can be known as contention window (CW) is an algorithm that is used to sort out contention problems that occur between different stations that plan to relay data simultaneously

[22]. In a simpler definition, it is the time when the network operates in contention mode [23]. When one station is in the backoff state, it will stand by on a supplementary number of time slots that are randomly selected. This random number must be larger than 0 and smaller than the contention window which is the maximum value [22]. While the station is waiting for the random number, it will continue to check whether the medium remains free or if any transmission from other stations has occurred. If the medium is still free at the end of the contention window, data will be transmitted however the backoff counter will be frozen and repeat the process if the medium is not free. As stated in the paper [22], there are difficulties in choosing the backoff window size. When the CW is small, collisions can occur as many stations attempt to send data simultaneously yet large values of CW can result in long backoff delays as few stations. Consequently, network performance can be degraded [22]. Therefore, the optimal backoff window size is studied.

Assuming that the sensing slots for the LTE node are equal to the WiFi node, $A^{(L)} = A^{(W)}$. Since the values are equivalent, equation (3) provides the recommended the size of backoff window for the LTE-LAA network $CW_{PF}^{(L)}$ to achieve fairness for both networks;

$$CW_{PF}^{(L)} = \frac{\tau_T^{(L)}}{\tau_T^{(W)}} \cdot CW^{(W)}$$

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

(3)

Where $T^{(L)}$ is the TXOP value in µs, $\tau_T^{(W)}$ is the holding time for any successful transmission at WiFi nodes, the optimal backoff window size is $CW_{PF}^{(L)}$, the successful transmission holding time for LTE-LAA nodes is $\tau_T^{(L)}$, whereas $CW^{(W)}$ is the backoff window size for WiFi nodes, D_{LTE} is the next transmission delay, where each LTE slot valued at 500 µs, $PL^{(W)}$ is the payload length, and $R^{(W)}$ is the WiFi transmission rate (Mbps). The value of TXOP $T^{(L)}$ and $CW^{(W)}$ impact the ideal initial backoff window size are based on equation (3).

Optimal Sensing Duration

According to a paper [8], even though the LTE-LAA LBT mechanism and WiFi distributed coordination function (DCF) have similar channel sensing processes, their channel sensing times differ [8][24]. A node must provide Clear Channel Access (CCA) utilizing an energy detection technique through a delay duration of Tf around 16 µs and a few time slots of length around 9 µs and the access priority class must be dependent on LTE-LAA.

Equation (4) gives the ideal value for LTE node sensing slots $A_{PF}^{(L)}$ to provide proportional fairness given that the two networks, WiFi and LTE have similar size of initial backoff window sizes;

$$A_{PF}^{(L)} = A^{(W)} - \frac{\ln\left(\frac{\tau_T^{(L)}}{\tau_T^{(W)}}\right)}{\ln \rho_A}$$

$$= A^{(W)} - \frac{\ln\left(\frac{\tau_T^{(L)} + D_{LTE}}{\frac{PL^{(W)}}{R^{(W)}} + OH}\right)}{\ln \rho_A}$$

(4)

Where the value of sensing slots for WiFi is known as $A^{(W)}$, whereas $A_{PF}^{(L)}$ is the ideal value of LTE-LAA sensing slots. During a successful connection for an LTE-LAA node, $\tau_T^{(L)}$ symbolizes its holding time, while $\tau_T^{(W)}$ is the holding time for a Wi-Fi node, and ρ_A is the steady-state point. Lastly, D_{LTE} is the delay for the next following transmission, where each LTE slot is anticipated to take 500 μs.

Adjustments of LTE-LAA Size of Initial Backoff Window and Sensing Duration

By using the MATLAB software, the two important parameters that are tuned to maintain the fair coexistence of the two systems are the initial backoff window size and sensing duration.

1) Tuning of the Size of the Initial Backoff Window

Table II presents the values of the size of the initial backoff window of LTE $CW^{(L)}$ that were applied, the values started from 16 as a minimum and increased to 96. Obtained from equation (4), the optimal value of the initial backoff window size of LTE-LAA, $CW_{PF}^{(L)}$ is 48 when $T^{(L)}$= 8 ms and $A^{(L)}$ = 2. The size of the initial backoff window of WiFi $CW^{(W)}$ is set to 16 in all simulations for tuning of initial backoff window size as this value is imposed as a fixed standard value of 16 in IEEE 802.11 standard [8][23].

TABLE II Tuning values for the size of the initial backoff window with $A^{(L)}$=2 and $T^{(L)}$=8 ms

$CW^{(W)}$	**$CW^{(L)}$**
16	16
16	26
16	36
16	46
16	48
16	56
16	66
16	76
16	86
16	96

2) **Tuning of Sensing Duration**

As for sensing duration, both values are initially at 2. The sensing duration for LTE $A^{(L)}$ is then increased to 10 as shown in Table III. The sensing duration of WiFi $A^{(W)}$ is set to be a fixed constant at 2 [8]. If the value of $A^{(W)}$ is equal to $A^{(L)}$, the trend of the graph will always remain the same. Using equation (4) $A_{PF}^{(L)}$, the value of optimal sensing duration for LTE-LAA is 3.7 when CW = 16.

TABLE III Tuning values for sensing duration when CW=16. $A^{(W)}$ is fixed at 2

A(W)	**A(L)**
2	2
2	3
2	3.7
2	4
2	5
2	6
2	7
2	8
2	10

Result And Discussion

In this section, results from the simulation will be presented and discussed to fulfill the objectives of this research.

1) The size of the Initial Backoff Window

From the results in Fig. 2, Fig. 3 and Fig. 4, it was found that the network airtime performance when $CW^{(L)} = 16$ and $CW^{(L)} = 96$ are similar, while it achieves a larger value of network airtime when the setting for $CW^{(L)}$ is at optimal. As given in (1), we can relate node airtime $\lambda_{out}^{(\Psi)}$ with the backoff window size $CW^{(\Psi)}$ as inversely proportional to one another. In this case, only the LTE-LAA node $CW^{(L)}$was tuned since $CW^{(W)}$is at standard value. Therefore, when the value $CW^{(L)}$ is greater, the LTE-LAA node airtime $\lambda_{out}^{(L)}$ is smaller. Consequently, the increase in the size of the initial backoff window value has caused the graph of LTE node airtime to drop.

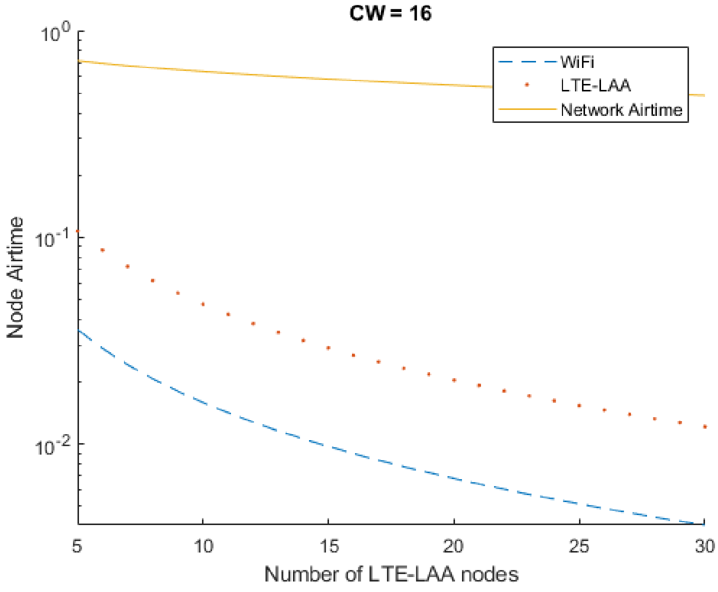

Fig. 2: The node airtime versus the LTE-LAA nodes number for CW(L) =16. Value of CW(W) = 16, A = 2 and T(L) = 8 ms

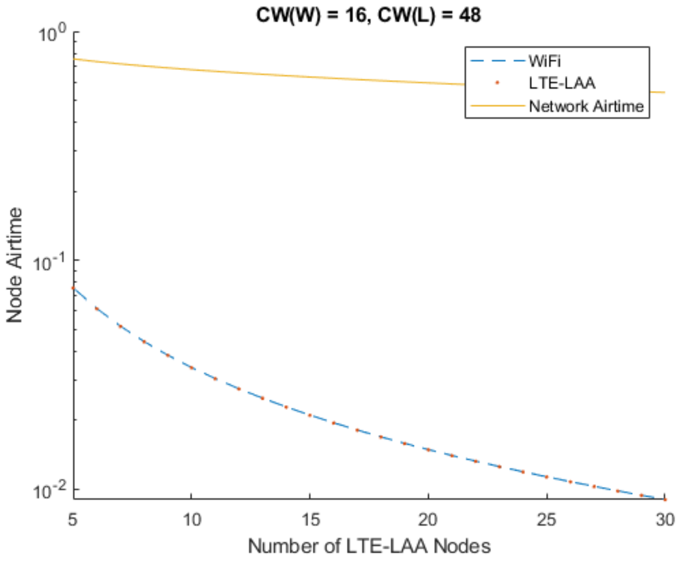

Fig. 3: The node airtime versus the LTE-LAA nodes number for CW(L) = 48. The value of CW(L) is optimal. Value of CW(W) = 16, A = 2 and T(L) = 8 ms

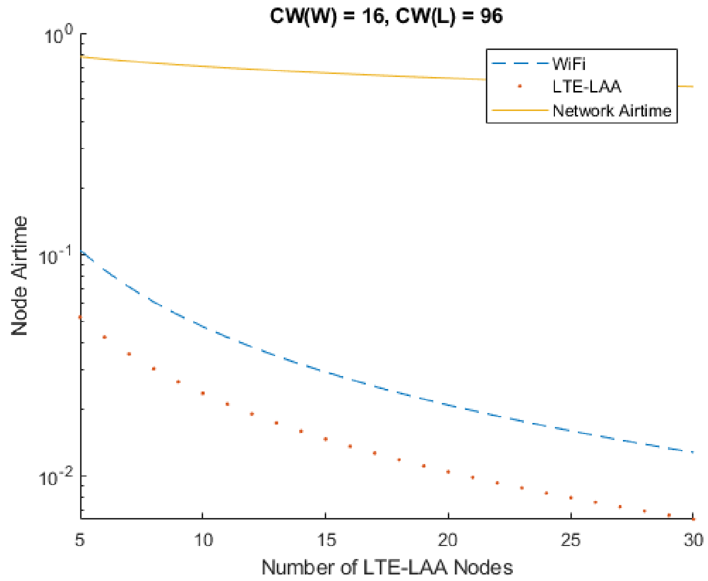

Fig. 4: The node airtime versus the LTE-LAA nodes number for CW(L) = 96. Value of CW(W) = 16, A = 2 and T(L) = 8 ms

The graphs for node airtime WiFi, $\lambda_{out}^{(W)}$ and node airtime LTE-LAA, $\lambda_{out}^{(L)}$ are nearly identical and have higher total network airtime, as shown in Fig. 3 when the value of the initial backoff window is at its best, $CW^{(L)} = CW_{PF}^{(L)}$. As stated in paper [8], proportionate fairness of the two networks' coexistence is attained when $\lambda^{(W)}$ and $\lambda^{(L)}$ are at identical ratios.

Therefore, the proportionality of the two networks' airtime performance is attained when the tuning for the size of the LTE-LAA initial backoff window is ideal $CW_{PF}^{(L)}$. The network airtime for the two networks' performance is assured at the same time. A longer value of TXOP $T^{(L)}$ will produce a larger value of network performance, as indicated in equation (3) since the greater value of $CW^{(L)}$ is necessary to maintain the performance with $CW^{(W)}$. Take note that $T^{(L)}$ = 8 ms and $A^{(L)}$ = 2 in this simulation.

2) Sensing Duration.

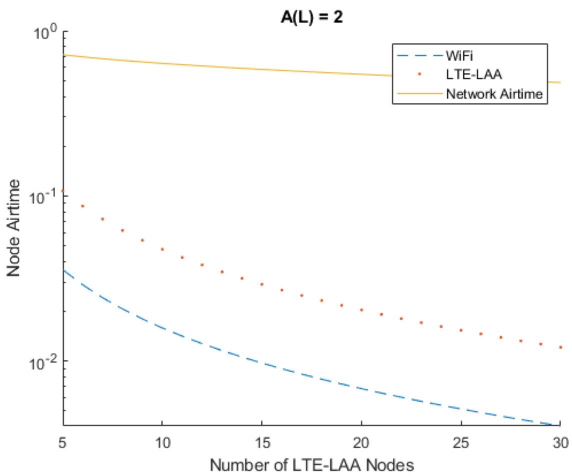

Fig. 5: The node airtime versus the LTE-LAA nodes number for A(L) = 2. Value of A(W) =2, CW =16

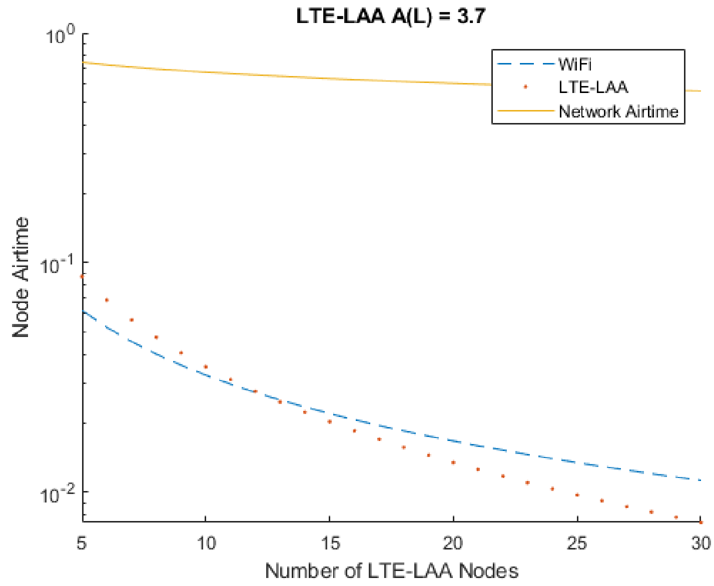

Fig. 6: The node airtime versus the LTE-LAA nodes number for A(L) = 3.7 at optimal. Value of A(W) =2, CW =16.

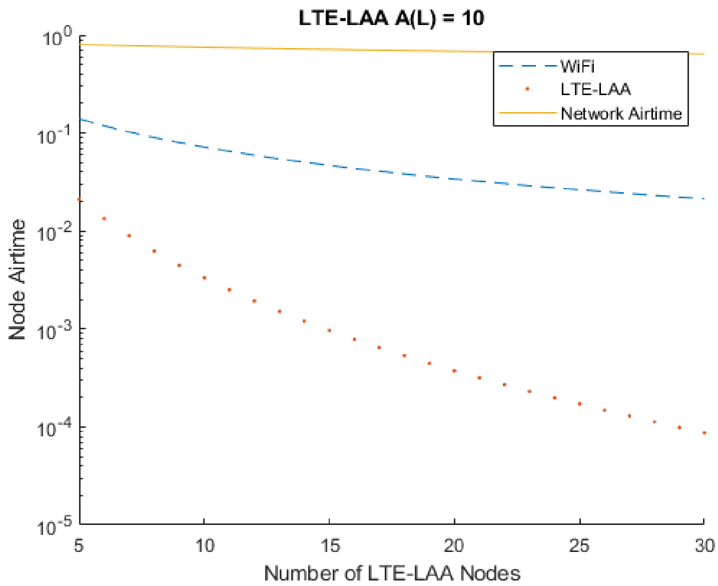

Fig. 7: The node airtime versus the LTE-LAA nodes number for A(L) = 10. Value of A(W) =2, CW =16.

When the value of $A^{(L)}$ is more than 4 with CW of16, the LTE-LAA and WiFi node airtime greatly diverge from one another, as seen by comparing Figs. 5 and 7. This is because there was an approximate error. According to a study by [8], this inaccuracy could be minimized by raising the value of CW while keeping the value of $A^{(L)}$ constant.

The two nodes achieved nearly the same values of node airtime although variations in network size as long as the number of time slots for LTE-LAA is set to the optimal setting $A_{PF}^{(L)}$, as shown in Fig. 6, with both graphs being close to one another. This contrasts with the uneven node airtimes of LTE-LAA and WiFi when $A^{(L)} \neq A_{PF}^{(L)}$.

Conclusion

To meet the objectives of this study, the sensing duration sensing slots $A^{(L)}$value and the size of the initial backoff window tuning $CW^{(L)}$ was performed to evaluate the performance of coexistence between LTE-LAA and WiFi. Based on the results obtained, it was found that when the value $CW^{(L)}$ is inadequate or redundant, collisions and degradation occurring can severely affect the overall network performance. Therefore, optimal values of both the size of the initial backoff window $CW_{PF}^{(L)}$and sensing slots numbers $A_{PF}^{(L)}$were tuned in the MATLAB simulation and comparisons were made between the existing values and optimal values. It was clear that optimal values of the size of the initial backoff window and the sensing duration for LTE have a significant effect on the airtime performance. When both parameters are tuned to optimal, $CW^{(L)} = CW_{PF}^{(L)}$ and $A^{(L)} = A_{PF}^{(L)}$, the best performance for LTE-LAA and WiFi coexistence is guaranteed.

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