IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2024.0429000

Towards Fair Spectrum Sharing: An Enhanced Fixed Waiting Time Model for LAA and Wi-Fi Networks Coexistence

MOAWIAH ALHULAYIL[1], (Member, IEEE), MIGUEL LÓPEZ-BENÍTEZ[2, 3], (Senior Member, IEEE), MOHAMMED ALAMMAR[4], (Member, IEEE), and ABDULRAHMAN AL AYIDH[4]

[1]Department of Electrical Engineering, Applied Science Private University, Amman 11937, Jordan.
[2]Department of Electrical Engineering and Electronics, University of Liverpool, Liverpool, L69 3GJ, United Kingdom.
[3]ARIES Research Centre, Antonio de Nebrija University, 28040 Madrid, Spain.
[4]Department of Electrical Engineering, King Khalid University, Abha 61421, Kingdom of Saudi Arabia.

Corresponding author: Moawiah Alhulayil (e-mail: m_alhulayil@asu.edu.jo).

This work was supported by the Deanship of Research and Graduate Studies at King Khalid University through Small group Research Project under grant number RGP1/388/46.

ABSTRACT This study addresses the challenge of fair spectrum sharing in unlicensed bands for Licensed Assisted Access (LAA) and Wi-Fi coexistence. Existing methods, particularly the 3GPP Category 4 Listen Before Talk (Cat 4 LBT) algorithm, fail to fully meet the fairness criteria due to limitations in dynamic Contention Window (CW) adjustments. To improve spectrum efficiency, we propose an Enhanced Fixed Waiting Time (Enhanced FWT) approach, which leverages a theoretical model of Wi-Fi ON periods to determine fixed waiting times for LAA networks. By employing the β distribution to represent Wi-Fi activity more accurately, this model avoids the need for dynamic CW adjustments. Simulation results demonstrate that Enhanced FWT method significantly enhances throughput compared to both the Cat 4 LBT and traditional empirical FWT methods, especially in dense network conditions. This approach, compliant with 3GPP fairness standards, shows promise for robust spectrum sharing, promoting fair LAA/Wi-Fi coexistence in unlicensed bands.

INDEX TERMS coexistence management, dynamic spectrum sharing, heterogeneous networks, licensed assisted access, ns-3.

I. INTRODUCTION

THE limited availability of licensed spectrum presents a major challenge in meeting the performance standards required for current and future cellular networks [1]. To conquer this challenge, several studies have been proposed enabling the transition of cellular networks from the licensed spectrum environment to a shared one [2]. Consequently, these studies are largely directed at ensuring compatible coexistence between cellular and Wi-Fi networks, particularly within the unlicensed 5 GHz band, due to the extensive deployment of legacy 802.11 networks. The unlicensed spectrum was initially leveraged for 3GPP Long Term Evolution (LTE) transmissions, offering increased capacity for mobile networks, and has been inevitably adopted by the coming 3GPP specifications [3], [4]. The use of unlicensed spectrum is considered in the development of 5G cellular communications (5G NR-U) [5].

Despite of the increased throughput and capacity achieved by deploying cellular networks over the unlicensed spectrum, several concerns arise because of this heterogeneous cellular/Wi-Fi coexistence. Specifically, the difference in Medium Access Control (MAC) layers between the two technologies presents a challenge: Wi-Fi utilises the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol, while cellular networks initially lacked a comparable sensing mechanism [6]. Therefore, running LTE and Wi-Fi on the same unlicensed band without a coordinated coexistence strategy could result in decreased Wi-Fi throughput.

To tackle this challenge, 3GPP Release 13 introduced the Licensed Assisted Access (LAA) approach to boost LTE networks' spectral efficiency and promote fair spectrum sharing with Wi-Fi networks [7]. This approach incorporates a channel access method called Listen Before Talk (LBT), similar to that used in Wi-Fi technology. It specifically employs a Carrier Aggregation (CA) scheme, combining carriers from both licensed and unlicensed bands. The LBT algorithm requires any Base Station (BS) or node to sense the channel for a Clear Channel Assessment (CCA) period before transmission, ensuring that transmission only occurs once an energy detection threshold is met. This modification in the PHY/MAC layers standards aims to support a fair cellular/Wi-Fi coexistence where BSs need to follow this sensing approach before transmission. However, within the framework of LAA and Wi-Fi coexistence on the 5 GHz band, 3GPP TR 36.889 defined fairness as the requirement that LAA should not degrade Wi-Fi throughput and latency beyond the level caused by an additional Wi-Fi operator [7]. Therefore, while proposing LAA mechanisms, this definition of fairness should be taken into consideration. Moreover, 3GPP TR 38.889 considered the LBT mechanism of LAA as the basis for the design of the newly regulated 6 GHz band [8].

Recent works, such as [9], explored advanced applications of cognitive radio in complex network architectures such as space-air-ground integrated networks with active Reconfigurable Intelligent Surface (RIS) and Non-Orthogonal Multiple Access (NOMA) capabilities. While this work focuses specifically on LAA/Wi-Fi coexistence in unlicensed bands, it aligns with the broader cognitive radio paradigm of enabling intelligent and adaptive spectrum access. Various approaches were introduced to promote fairness in LAA/Wi-Fi coexistence, concentrating on LAA design parameters including refining the energy detection threshold, modifying transmission durations, and selecting an optimal sensing time [10]–[12]. These parameters play a crucial role in ensuring fair coexistence between LAA and Wi-Fi networks. [13] investigated the effects of various design parameters on system performance for NR-U/Wi-Fi coexistence using the Category 4 LBT (Cat 4 LBT) algorithm. The results indicate that increasing the sensing range of a gNB enhances the performance of the Wi-Fi network, thought it negatively impacts the performance of the NR-U network. On the other hand, to enhance LAA throughput in an LAA/Wi-Fi coexistence scenario, [14] formulated an optimisation problem targeting the transmission probability and rate for each LAA station. The resulting numerical analysis shows that this optimisation yields a significant increase in LAA throughput. [15] introduced a Listen Before Receive (LBR) mechanism aimed at reducing collisions in LAA/Wi-Fi coexistence, addressing the impact of hidden and exposed nodes. The results indicate that adopting this coordinated approach leads to improved network performance. The authors in [16] suggested optimal settings for the Contention Window (CW) size, sensing durations and transmission opportunities of LAA to achieve proportional fairness between LTE-LAA and Wi-Fi coexistence. The results suggest that adjusting the initial CW size be the most effective strategy for achieving fair coexistence between LAA and Wi-Fi networks.

While this work focuses on fair spectrum sharing and coexistence between LAA and Wi-Fi networks, it is important to note that unlicensed spectrum use may also pose security risks such as jamming or spoofing attacks. These vulnerabilities have been discussed in the context of LAA/Wi-Fi coexistence in recent studies (e.g., [6] , [17]). Although security is beyond the scope of this study, it remains a critical topic for future research to complement coexistence mechanisms with resilience against adversarial behaviour.

This research addresses the need to create a coexistence mechanism that adheres to the 3GPP standards for fairness while enhancing the conventional Cat 4 LBT algorithm. The existing Cat 4 LBT algorithm, as specified in TR 36.889, does not fully meet the 3GPP fairness requirements when LAA and Wi-Fi networks operate together in the 5 GHz band [7]. This limitation leads to decreased Wi-Fi throughput due to the CW-based method employed in the Cat 4 LBT algorithm, as it will be discussed in Section II. To address this issue, this study proposes an LAA approach that facilitates fair coexistence by setting fixed waiting times for LAA, based on a theoretical model that incorporates Wi-Fi activity data.

The contributions of this work are summarised below:

- The 3GPP fairness definition is adopted in this work, employing a theoretical distribution model instead of an empirical one to accurately represent the existing Wi-Fi ON times, allowing for the determination of suitable fixed waiting times for LAA.
- In contrast to the standard 3GPP Cat 4 LBT algorithm, which adjusts the LAA CW size based on Hybrid Automatic Repeat Request (HARQ) feedback, this study introduces an innovative method that establishes fixed waiting times for LAA. This approach, rather than relying on the 3GPP CW-based scheme, uses a theoretical model of Wi-Fi activity statistics to meet the fairness criteria.
- The use of a fixed waiting time removes the need for a protocol to dynamically adapt the CW based on the experienced collision rate, which results in a simplified and more efficient overall coexistence protocol.

The paper is structured as follows. First, Section II begins with an illustration of the standard 3GPP Cat 4 LBT algorithm. Then Section III introduces a novel approach for setting the LAA waiting times using a theoretical model of Wi-Fi ON periods to facilitate fair coexistence between LAA and Wi-Fi networks. The methodology and system model are outlined in Section IV. The simulation results are presented and analysed in Section V. Lastly, the paper is concluded in Section VI.

II. CATEGORY 4 LBT (CAT 4 LBT) ALGORITHM

The 3GPP Cat 4 LBT algorithm utilises an approach that resembles the mechanism found in Wi-Fi technology. In particular, the algorithm incorporates a backoff process, as illustrated in Fig. 1. During this process, the channel is monitored for a CCA period to confirm its availability for transmission. Specifically, if the channel remains unoccupied for an initial CCA (iCCA) period (e.g., 34 μs), the LAA eNB is permitted to use the channel for transmission. Otherwise, a backoff process is initiated during the extended CCA (eCCA) phase. This process implies the random selection of $N \in [0, q-1]$, where

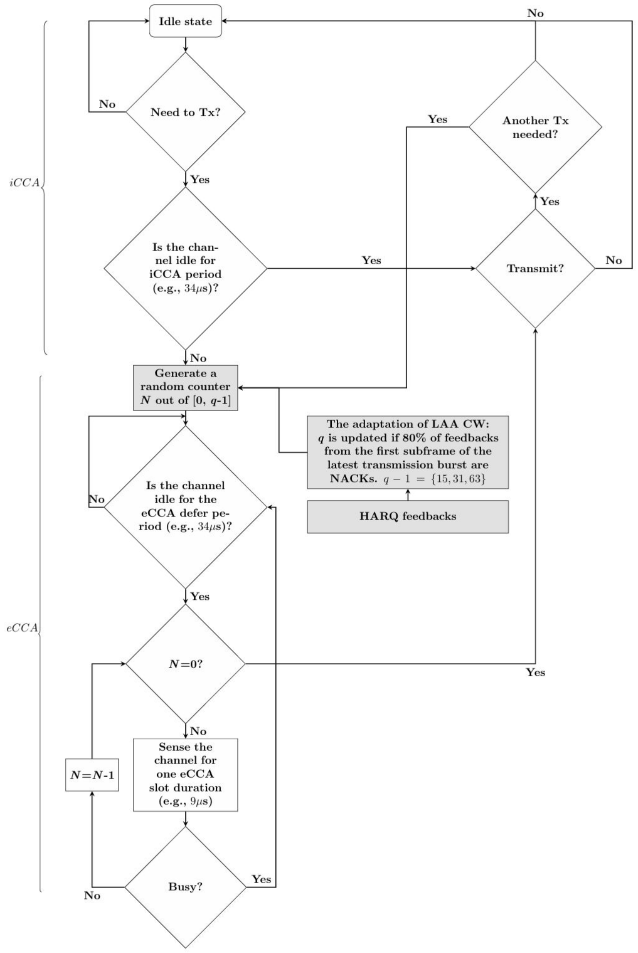


FIGURE 1. 3GPP Cat 4 LBT algorithm [7].

N specifies how many empty slots must be monitored before the transmission begins and $q\breve{}1$ denotes the upper bound of the LAA CW. The upper bound of the LAA CW is updated based on an exponential backoff. The LAA eNB monitors the channel for a duration equal to N times the CCA period (e.g., 9 μs). If the channel remains clear, the eCCA period is engaged, and N is decremented by one. When N reaches zero, the LAA eNB initiates transmission for a fixed adjustable Transmission Opportunity (TxOP) period, determined by the channel access priority class (refer to [18, Table 15.1.1-1] for details). For subsequent transmissions, the eCCA stage is repeated. The size of the LAA CW is determined by the channel access priority class, and the upper bound of the LAA CW $q-1$ is adjusted if 80% of the HARQ reports from the previous transmission are Negative Acknowledgments (NACKs). For instance, for channel access priority class 3, the upper bound options for the LAA CW are $\{15, 31, 63\}$.

Notably, the standard Cat 4 LBT algorithm adjusts the upper bound of the LAA CW without considering the existing Wi-Fi activity, which is not the most effective approach for ensuring fair coexistence. To address this, a novel method is proposed in this work to set the LAA waiting times based on the existing Wi-Fi activity statistics, thereby enhancing the performance of the Cat 4 LBT algorithm. This new approach will replace the shaded boxes shown in Fig. 1, improving the 3GPP Cat 4 LBT algorithm. A comprehensive explanation of the proposed method is provided in the following section.

III. ENHANCED FIXED WAITING TIME (Enhanced FWT) METHOD

In the Cat 4 LBT, the LAA eNB monitors the channel for a duration equal to N times the CCA slot period (e.g., 9 μs). Here, N is an integer selected randomly from a uniform distribution over the range $[0, q-1]$, where $q-1$ represents the upper limit of the LAA CW. This upper limit is adjusted based on HARQ reports to values of 15, 31 or 63. This randomness in selecting the number of idle slots ignoring the real activities of Wi-Fi network motivated the authors in [19] to configure a fixed waiting time (rather than random) for LAA based on the actual Wi-Fi activities. In particular, the empirical Cumulative Distribution Function (CDF) of the ON periods for the existing Wi-Fi network is used to establish a fixed waiting time for LAA, improving the performance compared to the dynamic mechanism in the Cat 4 LBT method. According to this approach, the LAA eNB waits for a duration of N times the CCA slot (9 μs), where N is determined by the empirical CDF of the Wi-Fi network's ON periods as follows

$$N = \lceil \frac{100\% \ of \ the \ empirical \ CDF \ of \ WiFi \ ON \ periods}{slot \ period} \rceil \tag{1}$$

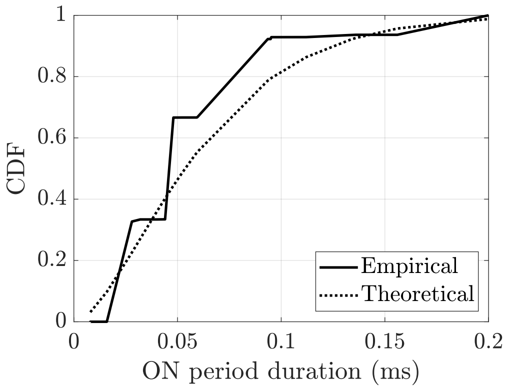
where $\lceil . \rceil$ is the ceil operator.

It is important to note that the fixed waiting time (FWT) method relies on the empirical CDF of the observed Wi-Fi ON times while the cellular network remains idle, meaning its parameter calculations are based on a limited set of empirical observations. This sample size may not be sufficient to accurately capture the true underlying distribution. By contrast, assuming an appropriate theoretical distribution can offer a closer approximation of the actual random process, provided the distribution is well-chosen. The empirical CDF represents only a small sample, while a carefully selected theoretical model can better describe the underlying random process that generates the Wi-Fi ON times. Thus, adopting a valid distribution model can be more effective than relying on an empirical CDF from experimental data alone. To address this, an Enhanced Fixed Waiting Time (Enhanced FWT) method is proposed in this work to improve upon the standard Cat 4 LBT by modeling Wi-Fi activities using the β distribution for the ON times, instead of the empirical CDF used in the FWT method. The β distribution is highly flexible and can represent almost any bounded random variable. This continuous probability distribution, defined over the interval $[0, 1]$, uses two positive shape parameters, α and β, defined as follows [20, eq. (4-48)]

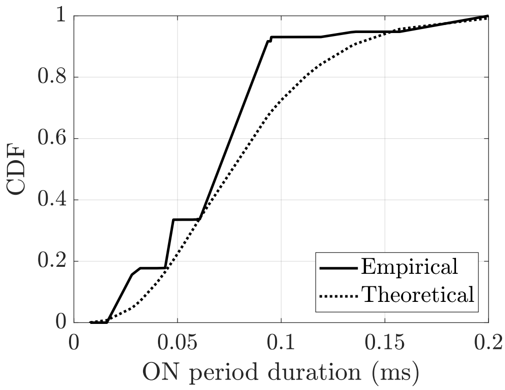
$$\alpha = \left[\frac{\mu(1-\mu)}{\sigma^2} - 1\right]\mu \tag{2}$$

$$\beta = \alpha\left[\frac{1}{\mu} - 1\right] \tag{3}$$

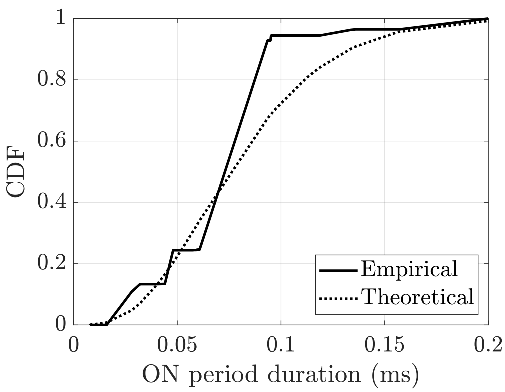
where μ and σ^2 are the mean and variance, respectively.



(a) $\lambda = 0.5$ packets/second.



(b) $\lambda = 1.5$ packets/second.



(c) $\lambda = 2.5$ packets/second.

FIGURE 2. Empirical and Theoretical CDFs of Wi-Fi ON periods across various traffic loads (0.5 MB packet size, with 20 STAs/UEs per operator).

To characterise the distribution of Wi-Fi ON times within the Enhanced FWT method, the β distribution is directly applied to the observed data without implementing normalisation. Although the β distribution is conventionally used for data constrained to a [0, 1] interval, the empirical Wi-Fi ON times in this study exhibit a naturally bounded and practical range, thus facilitating effective modeling without transformation. This approach circumvents the need for normalisation, preserving the data's fidelity by retaining its original scale. Moreover, employing the β distribution in this manner allows us to accurately capture the empirical distribution's shape while minimising preprocessing requirements, thereby preserving the intrinsic characteristics of the Wi-Fi ON times and enhancing the CDF modeling process.

The LAA network can evaluate the ON times of the existing Wi-Fi network. In particular, the LAA network can use the energy detection protocol to evaluate the actual activities of the existing Wi-Fi for reasonable periods of Wi-Fi [21]. The LAA network can exploit this evaluation to calculate the mean (μ) and variance (σ^2) of the Wi-Fi ON periods. Moreover, these variants (i.e., μ and σ^2) can be used to determine the shape parameters of β distribution using (2) and (3) for α and β, respectively. It is important to note that the β distribution parameters (α and β) can be dynamically estimated during system operation allowing the Enhanced FWT method to adapt in real time to varying Wi-Fi activity patterns. Techniques for traffic model estimation under realistic sensing conditions are available in the literature [21], [22]. Table 1 illustrates the procedure, which presents the respective variants and shape parameters of the theoretical CDF for Wi-Fi ON periods across different traffic loads as obtained from simulations. However, the shape parameters (α and β) listed in Table 1 are used to derive the theoretical CDFs of Wi-Fi ON times for the given traffic loads, as illustrated in Fig. 2. Thus, instead of using the CW-adaptation mechanism employed by the 3GPP Cat 4 LBT, the theoretical CDF of Wi-Fi ON times can be leveraged to establish the LAA waiting time based on the actual Wi-Fi network activity. Specifically, this waiting time is set to N times the CCA slot duration (9 μs), where N is determined by dividing the 100% percentile value of the theoretical CDF of Wi-Fi ON times by the CCA period (9 μs), as shown in Table 2.

The values listed in Table 2 for the FWT and Enhanced FWT method are derived from the empirical and theoretical CDFs of Wi-Fi ON periods, respectively. Specifically, in the Enhanced FWT method, the values are calculated from Fig. 2 by dividing the Wi-Fi ON periods corresponding to the 100% percentile of the CDF by the LAA slot period (9 μs) and rounding up the result. For instance, for a traffic load of $\lambda = 0.5$ packets/second, the Wi-Fi ON period at the 100% percentile of the CDF is approximately 197 μs. Dividing this by 9 μs and rounding up yields $N = 22$, as shown in Table 2. This procedure is applied to determine all values listed in Table 2.

In the FWT method, it should be emphasized that the values are derived from the empirical CDFs of Wi-Fi ON times rather than theoretical CDFs. As shown in Table 2, the FWT method produces a constant value of $N = 23$ across all traffic loads, which can be ascribed to the fact that the empirical

TABLE 1. The β distribution's variants and shape parameters corresponding to the existing Wi-Fi ON durations.

Arrival rate (λ) (packets/second)	Mean (μ) (μs)	Variance (σ^2) (μs)	α	β
0.5	63.6	2.0	1.83	26.95
1.5	81.0	1.5	3.94	44.69
2.5	79.6	1.2	4.78	55.27

CDF is obtained from a limited sample set and therefore potentially lacks of sufficient detail to accurately adjust the appropriate value of N. On the other hand, the Enhanced FWT method, which utilises the β distribution, adjusts the value of N appropriately for each traffic load, potentially leading to improved performance. Notably, the proposed method also simplifies the 3GPP Cat 4 LBT algorithm by eliminating the need for CW adaptation based on HARQ reports, as it removes the backoff process.

From a deployment perspective, the proposed Enhanced FWT method is compatible with current LAA protocol implementations and introduces minimal changes. Unlike Cat 4 LBT, which depends on HARQ feedback and CW adaptation, Enhanced FWT uses a fixed delay based on analytically estimated channel occupancy. This occupancy information can be obtained using passive monitoring techniques as described in [21] and [22], enabling seamless integration into existing LAA systems.

Although this study focuses on the 5 GHz band, it is important to note that the proposed Enhanced FWT method is equally applicable to coexistence scenarios involving future unlicensed bands and emerging Wi-Fi standards such as Wi-Fi 6 and Wi-Fi 7. These newer standards introduce physical layer enhancements such as higher modulation orders, OFDMA and multi-link operation, yet they retain the same contention-based channel access mechanism. Since the Enhanced FWT method models Wi-Fi ON periods based on this mechanism, its applicability remains sound. Moreover, the LAA protocol defined by 3GPP is intended for coexistence in unlicensed spectrum in general, making the proposed method relevant for deployments in the 6 GHz band (e.g., Wi-Fi 6E/7 coexistence) and even in the 60 GHz band (e.g., WiGig/802.11ad).

IV. METHODOLOGY

To assess the effectiveness of the method introduced in this study, the 3GPP fairness standard is considered. Specifically, the proposed method is evaluated to ensure that the LAA network does not negatively affect the Wi-Fi network's throughput and latency beyond the impact that would be caused by adding another Wi-Fi network on the same channel.

To satisfy the fairness definition, homogeneous coexistence is established by deploying two Wi-Fi networks on the same frequency band to monitor the activity patterns of the existing Wi-Fi network. The CDF of the Wi-Fi network's ON periods is then utilised to set the LAA waiting times according to the proposed approach. Subsequently, one of the Wi-Fi networks is substituted with an LAA network, facilitating LAA/Wi-Fi coexistence and enabling performance assessment under heterogeneous conditions.

In this study, the methodology incorporates 3GPP TR 36.889 to evaluate LAA/Wi-Fi coexistence performance, except for the CW updating rule, as the proposed LAA waiting time method is applied. The performance evaluations are conducted employing the ns-3 simulator with the integrated LAA extension, considering a single-floor indoor environment with two operators: Operator A (Wi-Fi) and Operator B (LAA). Both operators share a 20 MHz channel within the unlicensed 5 GHz band, as depicted in Fig. 3. The simulation environment includes multiple Access Points (APs) and eNodeBs (eNBs), each serving multiple users, resulting in realistic and dense network configurations. The setup here includes four APs for Operator A and four eNBs for Operator B, with each operator deploying 20 randomly placed stations (STAs) or User Equipments (UEs). A 2x2 MIMO configuration is used for all users and base stations. To model traffic in the downlink scenario, File Transfer Protocol (FTP) Model 1 is employed, simulating file transfers over User Datagram Protocol (UDP) based on a Poisson arrival process with an arrival rate of λ packets/second. File sizes are set to 0.5 MB, with arrival rates ($\lambda = 0.5, 1.5, 2.5$ packets/second) to produce varying load levels [7]. Table 3 compares the simulation parameters to the 3GPP reference scenario. The energy detection principle is applied, where Wi-Fi nodes recognise each other at -82 dBm and LAA nodes at -62 dBm, while LAA nodes recognise Wi-Fi nodes at -72 dBm. The simulation environment used in this study is based on the reference configuration defined by the ns-3 LAA module, which has been widely adopted in both academic research and 3GPP standardisation contributions [23], [24]. This standardised setup ensures comparability and reproducibility across studies. Moreover, similar simulation scenarios have been used in several recent works on LAA/Wi-Fi coexistence (e.g., [25]–[28]), demonstrating its relevance and applicability for evaluating coexistence mechanisms such as the proposed Enhanced FWT method. The network topology reflects the standard deployment scenario used in LAA/Wi-Fi coexistence studies and aligns with the configuration described in 3GPP TR 36.889, where Wi-Fi access points and LAA base stations coexist on the same spectrum, each serving multiple users. Such a setup is widely adopted in the literature and is representative of practical system deployments.

To examine the efficiency of the proposed Enhanced FWT method, its performance is evaluated against the standard 3GPP method using the fairness metrics (throughput and latency). Throughput refers to the volume of data successfully transmitted from the sender to the receiver over a defined time interval at the Internet Protocol (IP) layer, whereas latency is measured as the time it takes for a packet to reach the receiver from the sender.

It is worth noting that the simulation framework used in

TABLE 2. LAA waiting times with the Cat 4 LBT, FWT and Enhanced FWT methods across different traffic loads (9 μs slots, with 20 STAs/UEs per operator).

Method	Cat 4 LBT	FWT	Enhanced FWT
Features	• Backoff process. • The LAA CW upper bound is set independently of current Wi-Fi activity statistics.	• No backoff process. • The LAA waiting time is determined using the empirical CDF derived from current Wi-Fi activity statistics.	• No backoff process. • The LAA waiting time is determined using the theoretical CDF derived from current Wi-Fi activity statistics.
$\lambda = 0.5$ packets/second	$N \in [0, q-1]$ $q-1 = \{15, 31, 63\}$	$N = 23$	$N = 22$
$\lambda = 1.5$ packets/second	$N \in [0, q-1]$ $q-1 = \{15, 31, 63\}$	$N = 23$	$N = 20$
$\lambda = 2.5$ packets/second	$N \in [0, q-1]$ $q-1 = \{15, 31, 63\}$	$N = 23$	$N = 19$

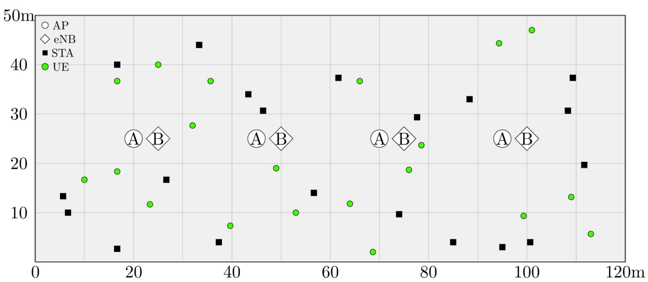


FIGURE 3. Indoor configuration with two operators, each with 4 cells and 5 STAs/UEs per cell.

TABLE 3. Simulation parameters.

	3GPP TR 36.889	ns-3 simulator
Network layout	Indoor scenario	Indoor scenario
System bandwidth	20 MHz	20 MHz
Carrier frequency	5 GHz	5 GHz (Ch.36)
Max. total BS Tx power	18/24 dBm	18 dBm
Max. total UE Tx power	18 dBm	18 dBm
Pathloss, shadowing & fading	ITU Indoor/Hotspot	IEEE 802.11n
Antenna pattern	2D omni-D	2D omni-D
Antenna height	6 m	6 m for LAA
UE antenna height	1.5 m	1.5 m for LAA
Antenna gain	5 dBi	5 dBi
UE antenna gain	0 dBi	0 dBi
UE dropping	Randomly	Randomly
Traffic model	FTP model 1 & 3	FTP model 1

this study, based on the ns-3 LAA module, has been widely employed in the literature and in 3GPP-related contributions, thus providing a reliable and standardised environment for performance evaluation.

V. SIMULATION RESULTS

This section investigates the coexistence of LAA and Wi-Fi networks using the Enhanced FWT method, focusing on fairness metrics for 95% of the users. Specifically, it shows the throughput values for each of the Wi-Fi and LAA networks individually, and also the combined overall throughput of both networks. Moreover, Wi-Fi latency is included. Notably, analyses were conducted for other percentiles, such as 90% and 100%, revealing similar trends across these scenarios. For conciseness, only the results for the 95% user percentile are shown here.

Fig. 4 shows the resulting Wi-Fi throughputs under different traffic load conditions, as determined by the methods applied. The reference case models a homogeneous coexistence scenario, where both operators deploy Wi-Fi networks (Operator A: Wi-Fi and Operator B: Wi-Fi). In contrast, heterogeneous coexistence scenarios (i.e., Wi-Fi and LAA) are represented by cases using the 3GPP Cat 4 LBT, FWT, and Enhanced FWT methods, in which a Wi-Fi network (Operator A) coexists with an LAA network (Operator B). According to the fairness guidelines, an effective LAA mechanism should allow the Wi-Fi network to maintain a performance level comparable to that of the reference case, without compromising overall network efficiency. The results indicate that, across all traffic loads, the 3GPP Cat 4 LBT method consistently underperforms relative to the reference case, thereby failing to meet the 3GPP fairness criteria. On the other hand, both the FWT and Enhanced FWT methods adhere to throughput fairness standards, providing significantly better throughput for the existing Wi-Fi network than the 3GPP Cat 4 LBT method. Moreover, with the deployment of an LAA network, these methods further improve Wi-Fi throughput compared to the deployment of an additional Wi-Fi network. This improvement is likely due to the FWT and Enhanced FWT methods' ability to set optimal LAA waiting times based on Wi-Fi activity patterns, thus enhancing the chances of accessing a clear channel without extended delays. As it can be noted, the Enhanced FWT method provides a higher throughput performance than the basic FWT method as a result of a finer tuning of the waiting time thanks to the use

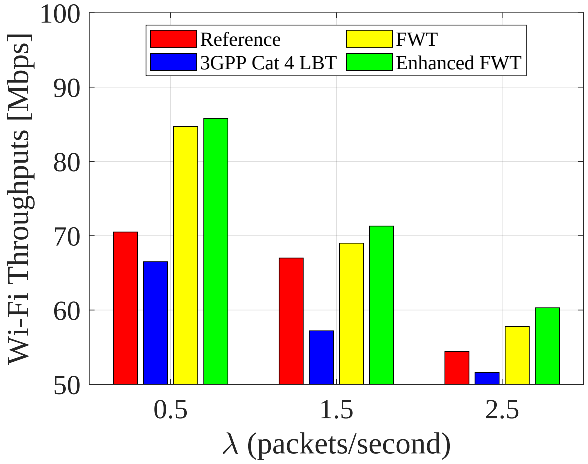


FIGURE 4. **Throughput performance of Wi-Fi using the assessed methods (20 STAs/UEs per operator).**

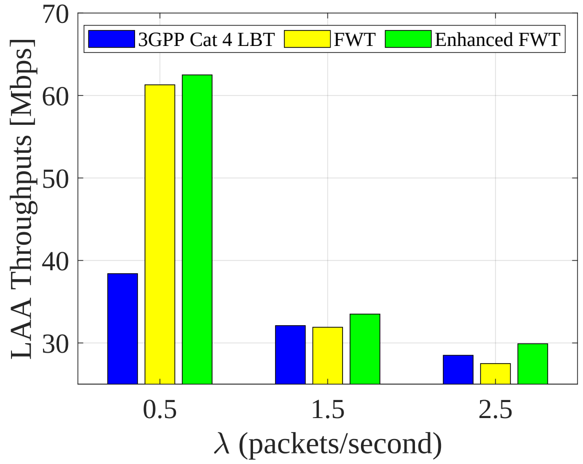


FIGURE 6. **Throughput performance of LAA using the assessed methods (20 STAs/UEs per operator).**

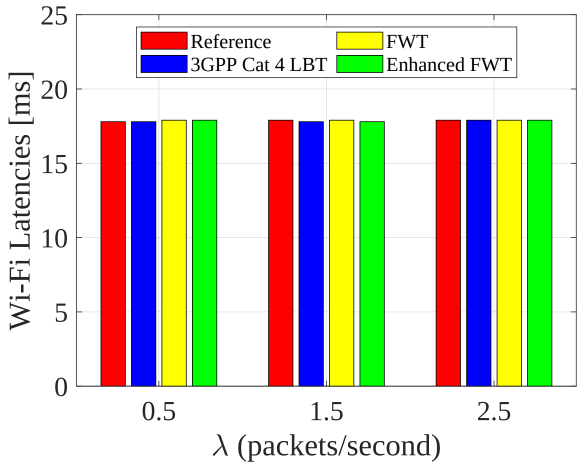


FIGURE 5. **Latency performance of Wi-Fi using the assessed methods (20 STAs/UEs per operator).**

of an appropriately selected theoretical model for the Wi-Fi ON times rather than the corresponding empirical distribution from a limited sample set.

Fig. 5 shows the latencies of the existing Wi-Fi network across various traffic loads for the methods evaluated. The results indicate that all methods yield latencies similar to the reference case, confirming that each approach, including the 3GPP Cat 4 LBT, satisfies the latency fairness criteria.

Fig. 6 presents the throughputs of the LAA network (Operator B) under various traffic load conditions for the evaluated methods. The results indicate that, in comparison to the 3GPP Cat 4 LBT method, both the FWT and Enhanced FWT methods deliver higher LAA throughputs at lower traffic loads ($\lambda = 0.5$ packets/second) and similar throughputs at medium and high traffic loads ($\lambda = 1.5$ and 2.5 packets/second). Thus, the gains in Wi-Fi throughputs observed with the FWT and Enhanced FWT methods (see Fig. 4) are achieved without compromising LAA throughputs. Therefore, the overall aggregated throughput for both networks is enhanced, as illustrated in Fig. 7. The Enhanced FWT method demonstrates substantial improvements in total aggregated throughput over the 3GPP Cat 4 LBT method, achieving increases of 41.4% (43.4 Mbps), 17.4% (15.5 Mbps) and 12.6% (10.1 Mbps) for traffic loads of $\lambda = 0.5$, 1.5 and 2.5 packets/second, respectively. Furthermore, the Enhanced FWT method provides improvements in total aggregated throughput over the FWT method, with gains of 1.6% (2.3 Mbps), 3.9% (3.9 Mbps) and 5.7% (4.9 Mbps) at traffic loads of $\lambda = 0.5$, 1.5 and 2.5 packets/second, respectively. This confirms that the β distribution is an appropriate choice, making the selected configuration based on this principle more effective than the empirical approach utilised in the FWT method. Interestingly, optimising the value of N for each traffic load (λ) in the Enhanced FWT method using the β distribution yields superior performance compared to the FWT method, which applies a constant $N = 23$ for all traffic loads (see Table 2). This can be attributed to the fact that the β model, through its mathematical formulation, provides a smoother representation for deriving the value of N from the CDF. In contrast, when N is determined using the experimental CDF, the resolution from empirically observed Wi-Fi times lacks the precision needed for such a refined selection of N. Moreover, it is noteworthy that the Enhanced FWT method achieves this improvement in total aggregated throughput without incurring any additional cost compared to the FWT method. Additionally, this throughput improvement grows with higher traffic loads. This encourages us to further examine the performance of the proposed Enhanced FWT method under higher traffic loads by increasing the number of users per AP/eNB.

Figs. 8 and 9 illustrate the results corresponding to Figs. 4 and 7 with a doubled user count in both networks. The key trends and previous findings are similarly applicable at this expanded network scale. Furthermore, in this scenario (with

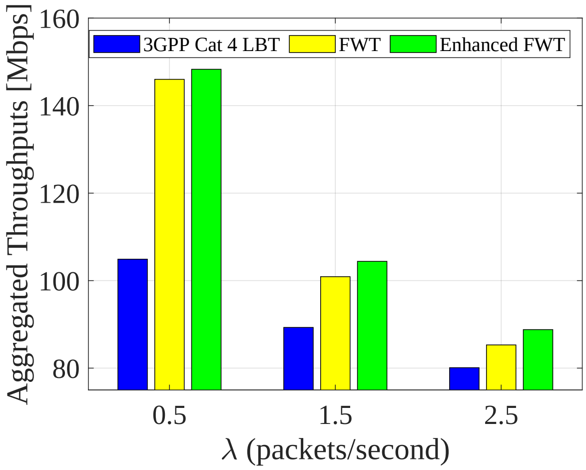


FIGURE 7. Aggregated throughput performance using the assessed methods (20 STAs/UEs per operator).

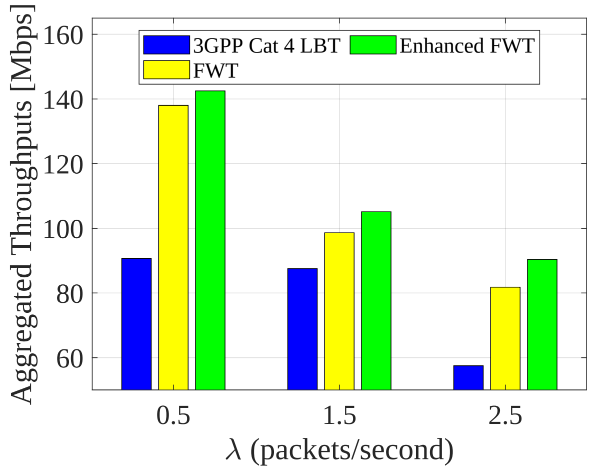


FIGURE 9. Aggregated throughput performance using the assessed methods (40 STAs/UEs per operator).

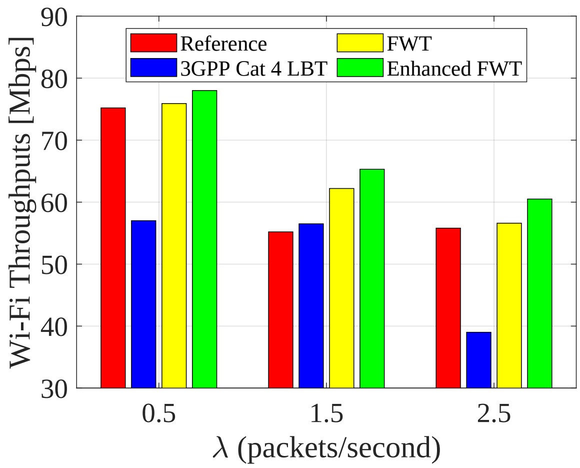


FIGURE 8. Throughput performance of Wi-Fi using the assessed methods (40 STAs/UEs per operator).

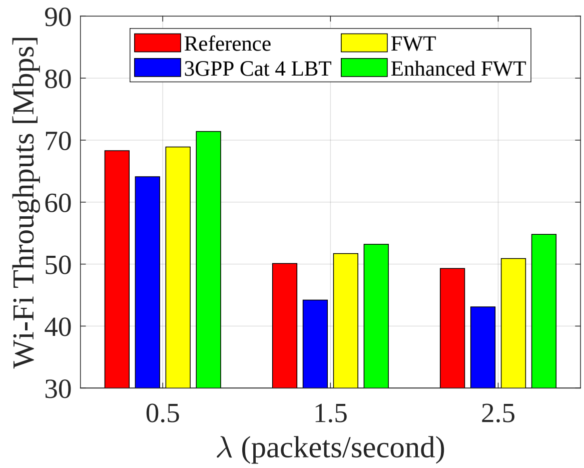


FIGURE 10. Throughput performance of Wi-Fi using the assessed methods (60 STAs/UEs per operator).

10 STAs/UEs per AP/eNB), the proposed Enhanced FWT method demonstrates significant gains in total aggregated throughput relative to the 3GPP Cat 4 LBT approach, with improvements of 57.1% (51.8 Mbps), 20.1% (17.6 Mbps) and 57.2% (32.9 Mbps) for traffic loads of $\lambda = 0.5$, 1.5 and 2.5 packets/second, respectively. Moreover, the Enhanced FWT method provides notable improvements in total aggregated throughput over the FWT method, achieving gains of 3.3% (4.5 Mbps), 6.6% (6.5 Mbps) and 10.5% (8.6 Mbps) for traffic loads of $\lambda = 0.5$, 1.5 and 2.5 packets/second, respectively. This makes the Enhanced FWT method particularly appealing for handling denser traffic loads compared to the 3GPP Cat 4 LBT and FWT methods.

To further assess scalability, the simulation setup is extended to a denser deployment with 60 users per operator (i.e., 15 STAs/UEs per AP/eNB). Figs. 10 and 11 present the resulting Wi-Fi and total aggregated throughputs under this configuration. As shown, the proposed Enhanced FWT method continues to yield substantial performance gains over the 3GPP Cat 4 LBT and the FWT methods. The Enhanced FWT model remains stable and effective despite the increased network density, thus confirming its scalability to more demanding coexistence scenarios.

In addition to improved throughput and fairness, the proposed Enhanced FWT method also demonstrates lower simulation execution time. Compared to Cat 4 LBT, which requires dynamic contention window adjustments and continuous HARQ-based feedback handling, the Enhanced FWT operates with a fixed waiting time derived from a theoretical distribution, reducing computational cost and complexity. In our experiments, the Enhanced FWT method consistently exhibited the shortest execution time, with reductions of approximately 20% compared to Cat 4 LBT and 10% compared to the empirical FWT approach. Therefore, the Enhanced

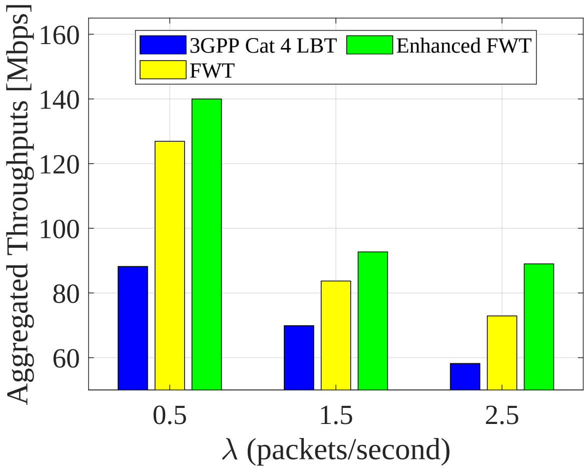


FIGURE 11. Aggregated throughput performance using the assessed methods (60 STAs/UEs per operator).

FWT method consistently achieves the lowest execution time due to its simplified logic, as it does not rely on per-packet backoff procedures nor HARQ-based adaptation of the CW. These efficiencies significantly reduce the computational cost and complexity, particularly in dense scenarios.

It is important to highlight that the proposed Enhanced FWT method builds upon the FWT approach introduced in our earlier work [19], where an extensive comparison against several state-of-the-art spectrum sharing mechanisms, including the standard 3GPP Cat 4 LBT method, was conducted. The results of [19] showed that the FWT approach provided a highly competitive performance across multiple scenarios. By enhancing the original FWT through the integration of a theoretically derived distribution model, this study achieves a finer tuning of LAA waiting times, which leads to improved fairness and throughput without increasing complexity. Although a full re-evaluation against all prior methods is not included here for brevity, the enhanced method inherently extends and outperforms the previously benchmarked techniques, thus reinforcing its practical relevance.

VI. CONCLUSION

A range of strategies have been developed to enable fair coexistence between LAA and Wi-Fi networks operating in unlicensed spectrum. While these approaches aim to satisfy 3GPP fairness requirements in terms of throughput and latency, the standard 3GPP Cat 4 LBT algorithm often fails to ensure fair performance-particularly for Wi-Fi networks, which tend to experience reduced throughput due to contention dynamics. This paper introduced a novel method that replaces the adaptive contention window mechanism with a fixed waiting time for LAA transmissions, derived from Wi-Fi activity patterns and analytically modelled ON periods using a β distribution. Simulation results demonstrated that the proposed Enhanced FWT approach significantly improves overall performance compared to both the 3GPP Cat 4 LBT method and the empirical FWT method. Notably, the Enhanced FWT method consistently achieved higher throughput and fairness, especially under dense user configurations. By simplifying access procedures and reducing computational complexity, the proposed method also offers practical advantages in terms of integration into existing LAA systems.

Future work may explore additional performance aspects such as energy efficiency, delay jitter and dynamic topology scenarios to further broaden the evaluation of coexistence mechanisms.

ACKNOWLEDGEMENT

The authors extend their appreciation to the Deanship of Research and Graduate Studies at King Khalid University for funding this work through Small group Research Project under grant number RGP1/388/46.

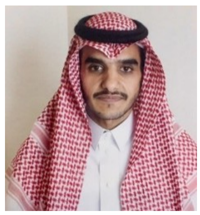
REFERENCES

[1] M. Matinmikko-Blue, S. Yrjölä, and P. Ahokangas, "Spectrum management for local mobile communication networks," *IEEE Commun. Mag.*, vol. 61, no. 7, pp. 60–66, Jul. 2023.
[2] Y. Lin *et al.*, "Fair and efficient spectrum sharing in unlicensed bands: Does number of links matter?" *IEEE Trans. Veh. Technol.*, vol. 72, no. 7, pp. 9459–9471, Jul. 2023.
[3] Y. Kakkad *et al.*, "Optimal 3GPP fairness parameters in 5G NR unlicensed (NR-U) and WiFi coexistence," *IEEE Trans. Veh. Technol.*, vol. 72, no. 4, pp. 5373–5377, Apr. 2023.
[4] A. M. H. Alibraheemi *et al.*, "A survey of resource management in D2D communication for B5G networks," *IEEE Access*, vol. 11, pp. 7892–7923, Jan. 2023.
[5] 3rd Generation Partnership Project, "Technical specification group radio access network; study on NR-based access to unlicensed spectrum (Release 16)," 3GPP, Tech. Rep. 3GPP TR 36.889, Dec. 2018, v16.0.0.
[6] I. Samy *et al.*, "Misbehavior detection in Wi-Fi/LTE coexistence over unlicensed bands," *IEEE Trans. Mobile Comput.*, vol. 22, no. 8, pp. 4773–4791, Aug. 2023.
[7] 3rd Generation Partnership Project, "Technical specification group radio access network; study on licensed-assisted access to unlicensed spectrum (Release 13)," 3GPP, Tech. Rep. 3GPP TR 36.889, Jun. 2015, v13.0.0.
[8] Federal Communications Commission (FCC), "Unlicensed use of the 6 GHz band," https://docs.fcc.gov/public/attachments/FCC-20-51A1_Rcd.pdf, Apr. 2020.
[9] J. Li *et al.*, "Active RIS-aided NOMA-enabled space-air-ground integrated networks with cognitive radio," *IEEE J. Sel. Areas Commun.*, vol. 43, no. 1, pp. 314–333, Jan. 2025.
[10] J. Yuan *et al.*, "Adaptive channel detection for full-duplex IAB systems on unlicensed bands," *IEEE Trans. Veh. Technol.*, vol. 72, no. 8, pp. 10 604–10 616, Aug. 2023.
[11] J. Peng *et al.*, "3GPP fairness constrained throughput optimization for 5G NR-U and WiFi coexistence in the unlicensed spectrum," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2022, pp. 1779–1784.
[12] H. Zhou, Y. Deng, and A. Nallanathan, "Novel listen-before-talk access scheme with adaptive backoff procedure for uplink centric broadband communication," *IEEE Internet Things J.*, vol. 10, no. 22, pp. 19 981–19 992, Nov. 2023.
[13] Q. Ren, B. Wang, J. Zheng, and Y. Zhang, "Performance modeling of an NR-U and WiFi coexistence system using the NR-U category-4 LBT procedure and WiFi DCF mechanism in the presence of hidden nodes," *IEEE Trans. Veh. Technol.*, vol. 72, no. 11, pp. 14 801–14 814, Nov. 2023.
[14] R. Saleem, S. A. Alvi, and S. Durrani, "Performance-fairness trade-off for Wi-Fi and LTE-LAA coexistence," *IEEE Access*, vol. 9, pp. 62 446–62 459, Apr. 2021.
[15] C.-Y. Huang *et al.*, "Listen before receive (LBR) assisted network access in LAA and WiFi heterogeneous networks," *IEEE Access*, vol. 9, pp. 43 845–43 861, Mar. 2021.
[16] Y. Gao and S. Roy, "Achieving proportional fairness for LTE-LAA and Wi-Fi coexistence in unlicensed spectrum," *IEEE Trans. Wireless Commun.*, vol. 19, no. 5, pp. 3390–3404, May 2020.

[17] S. Dongre and H. Rahbari, "Fair and secure 5G and Wi-Fi coexistence using robust implicit channel coordination," *IEEE Trans. Inf. Forensics Security*, vol. 19, pp. 6679–6692, Jul. 2024.
[18] 3rd Generation Partnership Project, "Technical specification group radio access network; LTE; evolved universal terrestrial radio access (E-UTRA); physical layer procedures (Release 13)," 3GPP, Tech. Rep. 3GPP TS 36.213, Apr. 2020, v13.16.0.
[19] M. Alhulayil and M. López-Benítez, "Novel LAA waiting and transmission time configuration methods for improved LTE-LAA/Wi-Fi coexistence over unlicensed bands," *IEEE Access*, vol. 8, pp. 162 373–162 393, Sep. 2020.
[20] A. Papoulis and S. U. Pillai, *Probability, random variables and stochastic processes*, 4th ed. McGraw Hill, 2001.
[21] O. H. Toma, M. López-Benítez, D. K. Patel, and K. Umebayashi, "Estimation of primary channel activity statistics in cognitive radio based on imperfect spectrum sensing," *IEEE Trans. Commun.*, vol. 68, no. 4, pp. 2016–2031, Apr. 2020.
[22] O. H. Toma and M. López-Benítez, "Traffic learning: A deep learning approach for obtaining accurate statistical information of the channel traffic in spectrum sharing systems," *IEEE Access*, vol. 9, pp. 124 324–124 336, Sep. 2021.
[23] L. Giupponi *et al.*, "Simulating LTE and Wi-Fi coexistence in unlicensed spectrum with ns-3," 2016, *arXiv: 1604.06826*. [Online]. Available: https://arxiv.org/abs/1604.06826
[24] B. Bojović, L. Giupponi, Z. Ali and M. Miozzo, "Evaluating unlicensed LTE technologies: LAA vs LTE-U," *IEEE Access*, vol. 7, pp. 89 714–89 751, Jul. 2019.
[25] Z. Ali *et al.*, "On fairness evaluation: LTE-U vs. LAA," in *Proc. 14th ACM Int. Symp. Mobility Manage. Wireless Access (MobiWac)*, Floriana, Malta, Nov. 2016, pp. 136–168.
[26] A. M. El-Shal *et al.*, "Machine learning-based module for monitoring LTE/WiFi coexistence networks dynamics," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, Montreal, QC, Canada, Jun. 2021, pp. 1–6.
[27] Y. Liu *et al.*, "Channel access optimization in unlicensed spectrum for downlink URLLC: Centralized and federated DRL approaches," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 7, pp. 2208–2222, Jul. 2023.
[28] Y. Liu *et al.*, "Machine learning for 6G enhanced ultra-reliable and low-latency services," *IEEE Wireless Commun.*, vol. 30, no. 2, pp. 48–54, Apr. 2023.

MOAWIAH ALHULAYIL (S'20, M'22) received the BSc and MSc degrees in Electrical Engineering from Jordan University of Science and Technology, Jordan in 2011 and 2014, respectively, and the PhD degree in Electrical Engineering and Electronics from University of Liverpool, UK in 2021. He became an Assistant Professor with the Department of Electrical Engineering, Applied Science Private University (ASU), Jordan since October 2021. From 2023 to 2024, he was the Head of Electrical Engineering Department, Faculty of Engineering & Technology, ASU, Jordan. From August 2022 to September 2022, he was a visiting researcher at the Department of Electrical Engineering and Electronics, University of Liverpool, UK. From June 2018 to July 2018, he was a visiting researcher at Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Barcelona, Spain. From 2017 to 2019, he was a Graduate Teaching Assistant in the Department of Electrical Engineering and Electronics, University of Liverpool, UK. His research interests include wireless cooperative networks, URLLC communications, high-frequency wireless systems, cognitive radio, dynamic spectrum, and heterogeneous networks. He also serves as a peer reviewer for several reputable international journals in the field of wireless communications and networking.

MIGUEL LÓPEZ-BENÍTEZ (S'08, M'12, SM'17) received the BSc and MSc degrees (both with Distinction) in Telecommunication Engineering from Miguel Hernández University, Elche, Spain in 2003 and 2006, respectively, and the PhD degree (*summa cum laude*) in Telecommunication Engineering from the Technical University of Catalonia, Barcelona, Spain in 2011. From 2011 to 2013, he was a Research Fellow with the Centre for Communication Systems Research, University of Surrey, Guildford, UK. In 2013, he became a Lecturer (Assistant Professor) with the Department of Electrical Engineering and Electronics, University of Liverpool, UK, where he has been a Senior Lecturer (Associate Professor) since 2018. His research interests include the field of wireless communications and networking, with special emphasis on mobile communications and dynamic spectrum access in cognitive radio systems. He has been the Principal Investigator or Co-Investigator of research projects funded by the EPSRC, British Council, and Royal Society, and has also been involved in the European-funded projects AROMA, NEWCOM++, FARAMIR, QoSMOS, and CoRaSat. He has been a member of the Organising Committee for the IEEE WCNC International Workshop on Smart Spectrum since 2015 and is currently an Associate Editor of IEEE Access, IET Communications, and Wireless Communications and Mobile Computing. Personal website at http://www.lopezbenitez.es.



MOHAMMED ALAMMAR (S'20, M'23) received the degrees of BSc in electrical engineering from the King Khalid University, KSA, in 2012 ,and MSc in electrical engineering from the University of Dayton, USA, in 2016. Additionally, the PhD degree in Electrical Engineering and Electronics from the University of Liverpool, UK, in 2023. He became a Lecturer (Assistant Professor) since October 2023 with the Department of Electrical Engineering, King Khalid University. From 2012 to 2018, he was a Graduate Teaching Assistant with the Department of Electrical Engineering, King Khalid University. From 2019 to 2022, he was a Senior Teaching Assistant (Assistant Lecturer) with the Department of Electrical Engineering, King Khalid University. His research interests include wireless communication and networking (with special emphasis on wireless sensor networks, cognitive radio and dynamic spectrum), Image Processing and Signal Processing.

ABDULRAHMAN AL AYIDH received his bachelor's degree in electrical engineering (Second honour) from King Khalid University, Abha, Saudi Arabia in 2014, and MSc (Distinction) in Telecommunication and Wireless Systems from University of Liverpool, Liverpool, UK in 2018. He obtained a PhD degree from the University of Glasgow, Glasgow, UK in 2022. His research interests include wireless communication systems, massive MIMO, cell free massive MIMO systems, hybrid beam-forming techniques, ultra-reliable and low-latency communications, and wireless networked control system.