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Delivering Fairness and QoS Guarantees for LTE/Wi-Fi Coexistence Under LAA Operation

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ABSTRACT Licensed assisted access (LAA) enables the coexistence of long-term evolution (LTE) and Wi-Fi in unlicensed bands, while potentially offering improved coverage and data rates. However, cooperation with the conventional random-access protocols that employ listen-before-talk (LBT) considerations makes meeting the LTE performance requirements difficult, since delay and throughput guarantees should be delivered. In this paper, we propose a novel channel sharing mechanism for the LAA system that is capable of simultaneously providing the fairness of resource allocation across the competing LTE and Wi-Fi sessions as well as satisfying the quality-of-service guarantees of the LTE sessions in terms of their upper delay bound and throughput. Our proposal is based on two key mechanisms: 1) LAA connection admission control for the LTE sessions and 2) adaptive duty cycle resource division. The only external information necessary for the intended operation is the current number of active Wi-Fi sessions inferred by monitoring the shared channel. In the proposed scheme, LAA-enabled LTE base station fully controls the shared environment by dynamically adjusting the time allocations for both Wi-Fi and LTE technologies, while only admitting those LTE connections that should not interfere with Wi-Fi more than another Wi-Fi access point operating on the same channel would. To characterize the key performance trade-offs pertaining to the proposed operation, we develop a new analytical model. We then comprehensively investigate the performance of the developed channel sharing mechanism by confirming that it allows to achieve a high degree of fairness between the LTE and Wi-Fi connections as well as provides guarantees in terms of upper delay bound and throughput for the admitted LTE sessions. We also demonstrate that our scheme outperforms a typical LBT-based LAA implementation.

INDEX TERMS LAA, long-term evolution (LTE), IEEE 802.11, QoS, fairness.

I. INTRODUCTION

The numbers of hand-held devices have increased dramatically over the past decade [1] followed by a tremendous traffic growth brought by the hungry spectrum consumers [2]. The anticipated lack of licensed spectrum for supporting the accelerating traffic demands forces vendors and standardization bodies to seek for new bands and efficiently explore the available ones. The foreseen solutions include the use of higher frequencies, such as millimeter wave bands [3], where more abundant spectrum is available, temporary licensing of spectrum (Licensed Shared Access, LSA [4], [5]), and entering the competition in shared Industrial, Scientific, and Medial (ISM) bands (Licensed Assisted Access, LAA [6], [7]). Among these options, the latter promises faster time to market and can be implemented as part of the long-term evolution-advanced (LTE-A) technology by 3GPP, thus offering an appealing cost-effective solution for network operators [8].

More specifically, LAA has been introduced in 3GPP Release 13 as part of LTE-A [9]. It employs carrier aggregation in the downlink to combine LTE in unlicensed spectrum with LTE in the licensed bands. According to the recent performance evaluation campaigns, this spectrum aggregation solution potentially promises higher data rates as well as more responsive user experience [10]. For example, a mobile operator using LAA can support Gigabit-Class LTE with as little as 20MHz of licensed spectrum. By maintaining a persistent anchor in the licensed spectrum that carries control and signaling information, user experience is promised to be made more seamless and reliable [11].

The use of additional frequency bands of licensed spectrum is a straightforward way to improve the capacity of the LTE system. However, vendors and cellular operators maintain that the available licensed bands may not be sufficient to satisfy the growing mobile traffic demand [12], [13]. To address this issue, in addition to the development of new millimeter-wave (mmWave) radio access technology [3] various approaches were considered, ranging from careful spectrum management by network virtualization [14] to temporary licensing of bands [15] for operation in unlicensed frequencies [16].

The amount of unlicensed spectrum available below 6GHz is around 500MHz, which may potentially offer a substantial capacity boost to the current cellular systems. However, most of the unlicensed bandwidth is concentrated in 2.4GHz and 5.8GHz ISM frequencies that are currently utilized globally by IEEE 802.11 wireless local area networks (WLANs). Enabling LTE operation in these bands naturally leads to a challenge of coexistence between random- and schedule-based access systems. Recently, vendors including Ericsson, Qualcomm, and Huawei as well as operators, such as SK Telecom, Verizon, and T-Mobile, invested significant efforts into the LAA technology [12], [13], [17], [18]. In 2017, Huawei, Vodafone, and Qualcomm launched their first commercial LAA network [18].

A. RELATED WORK

A critical requirement for LTE/Wi-Fi coexistence is that one LAA-enabled LTE base station (LAA BS) should not interfere with the existing Wi-Fi access points (APs) more than another single Wi-Fi AP operating at the same channel would [9], [11]. There has been a number of attempts to propose coexistence schemes for LTE and Wi-Fi systems operating over the same channel in the ISM bands. These approaches can be classified into two main categories, random access and schedule-based schemes [19]. The ones belonging to the first category introduce an additional layer into the LTE protocol stack to enable the listen-before-talk (LBT) functionality at the LAA BS [20]–[22]. Individual solutions vary from simple carrier sense multiple access (CSMA) schemes to complex 802.11-like random access mechanisms with an adaptive choice of parameters [23]–[25]. Operating in the LBT mode, LAA could provide fair division of the available spectrum between the LTE and the Wi-Fi components, thus satisfying the requirement of fairness as formulated in [9]. Particularly, it has been shown that under certain conditions even simpler LBT schemes may enforce fairness across competing sessions [25], [26].

The use of LBT-based LAA operation makes it complicated to employ one of the most attractive features of LTE, that is, provisioning of quality-of-service (QoS) guarantees. Indeed, as long as both Wi-Fi and LTE compete for the shared resources, no strict delay constraints can be met due to the intrinsic properties of the CSMA protocol family. Furthermore, as one may observe, direct competition between LTE and Wi-Fi may not be needed to achieve fairness, since LAA BS may be granted full control of the shared spectrum. Hence, instead of competing for resources with Wi-Fi, LTE may manage the resource allocation between Wi-Fi and LTE, thus dividing them in a fair manner while keeping track of the number of concurrent LTE and Wi-Fi sessions in proximity of the LAA BS. Following this schedule-based operational mode, not only fairness but also performance guarantees could be delivered.

The first step towards QoS-aware medium access control (MAC) protocol in LAA environments has been taken in [27], where the authors advocated for the use of schedule-based system to enable different levels of Wi-Fi protection. The latter is achieved by using LTE BS as a universal agent deciding on the channel division between Wi-Fi and LTE. Following the duty cycle based operation, where LAA BS seizes and frees the shared channel for certain periods of time, fairness may be enforced. The associated optimization framework in [27] utilizes appropriate input parameters and maximizes the channel rate. Several enhancements of this scheme have already been proposed in literature, including Q-learning mechanism for optimized duty cycle selection [28] and proportional fair allocation across flows [29]. However, the duty cycle based schemes reported so far do not allow for offering performance guarantees to the LTE connections as all of the arriving sessions are admitted and no differentiation between the LTE traffic classes is made.

B. OUR CONTRIBUTIONS

In this paper, we propose a novel channel sharing mechanism for the LAA environment, which is capable of fair resource division between the Wi-Fi AP and the LTE BS, while can at the same time provide performance guarantees to the LTE flows. The proposed scheme builds on top of the schedule-based approach originally elaborated in [19] and introduces two novel algorithms that are crucial for supporting LTE QoS in dynamic traffic conditions: (i) LAA connection admission control (CAC) and (ii) dynamic duty cycle adaptation.

The former ensures that the number of admitted LTE sessions is such that fair resource allocation between the Wi-Fi and LAA sessions is enforced, while the throughput guarantees are offered to the admitted LTE flows. The second mechanism dynamically adjusts the duty cycle duration to meet the upper delay bound requirements of the LTE sessions. To enable these features, an LAA BS is assumed to monitor the shared channel environment by keeping track of the number of Wi-Fi sessions. As a result, the proposed system does not require co-location of the Wi-Fi AP and the LAA BS.

We comprehensively study the performance of the proposed scheme by using a mixture of developed simulation and analytical models to demonstrate that:

- the proposed mechanism allows to achieve a high degree of fairness between the Wi-Fi and LAA sessions, while at the same time providing guarantees in terms of upper delay bound and throughput for the admitted LAA sessions;

- LAA CAC and adaptive duty cycle algorithms are mandatory to maintain the required QoS-aware operation of the proposed channel sharing mechanism;
- the fraction of time that the system spends in QoS violation regime caused by imperfect estimation of the number of Wi-Fi sessions (and having no control over their acceptance) is below 1% under high load conditions.

The rest of this paper is organized as follows. In Section II, we review the current status of the LAA technology. The proposed channel sharing mechanism is introduced in Section III. Our performance evaluation model is developed in Section IV. We assess the performance of the proposed LAA system in Section V. The conclusions are drawn in the last section.

II. CURRENT LAA ARCHITECTURE IN 3GPP

A. GENERAL SYSTEM DESIGN

Opportunistic use of unlicensed spectrum is becoming an important consideration for operators to meet the growing traffic demand. 3GPP together with IEEE, Wi-Fi Alliance, Wi-Fi manufactures, and other stakeholders have contributed significantly to analyzing new spectrum coexistence techniques starting from their Release 12. The success of the first tests on interworking between LTE and WLAN prompted 3GPP to deepen these coexistence studies. New architectures, interfaces, and protocols have been thus designed, leading to an increase in throughput of over 70% as compared to the use of Wi-Fi. Despite all these benefits, improvements for Wi-Fi under mobile and roaming scenarios are further required. Vendors and standardization bodies see value for the network operators to use unlicensed spectrum primarily in a unified network setup, in order to offer operational cost savings, improved spectral efficiency, and better user experience.

Starting with Release 13, 3GPP has decided to undertake a dedicated study on LAA, to equip consumers and operators with a new technique for improved user experience in the unlicensed spectrum, while coexisting at the same time with all of the current technologies in the 5GHz unlicensed bands, see Fig. 1. The goal of LAA is to maintain high performance in the licensed spectrum with LTE technology as well as employ the secondary carrier in the unlicensed frequencies for data rate boosting. The central focus of the studies was set on fair sharing and coexistence with Wi-Fi, where the criterion used to ensure such coexistence has been that the *LAA BS does not affect the existing Wi-Fi neighbors more than another Wi-Fi AP operating over the same channel would*. Another objective of LAA design is to offer a one-stop global solution that would allow for compliance with regional regulatory requirements and maintain effective and fair coexistence of LAA networks deployed by different operators.

Two main frequency bands of interest for LAA are ISM 2.4 and 5GHz. The latter has 150MHz of unlicensed spectrum available globally, which is 1.5 times more than in the 2.4GHz

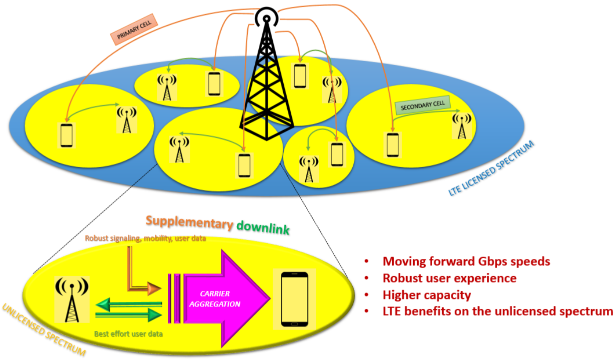


FIGURE 1. Concept of LAA by 3GPP.

band. Today, in Japan, Europe, India, and the US, the frequencies between 455 and 555MHz are available as well, and promise additional business opportunities. To ensure seamless coexistence with other technologies already operating at these frequencies, many countries impose constraints on power transmission in the unlicensed bands and may also dictate limitations on channel access procedures. Since 3GPP aims at global coverage of the LAA technology, an important requirement is to not only respect regulatory restrictions set by different countries but also allow for sufficient transmit power to enable both indoor and outdoor deployments. The use of ISM bands by LAA gives rise to potential interference problems, thus making the co-existence of LTE and Wi-Fi cumbersome.

The coexistence mechanisms have been evaluated by RAN1 of 3GPP and defined in TR 36.889 [9]. To address the aforementioned issues raised by the coexistence between licensed- and unlicensed-band systems, the following functionality has been proposed in 3GPP Release 13 for the conceptualization of LAA: discontinuous transmission, carrier selection, carrier aggregation, and LBT provisions:

- *Carrier Aggregation (CA).* CA is a key technique that enables the aggregation of multiple Component Carriers (CC) for LTE-A transmissions, downlink and uplink. It permits the LTE users to increase their effective transmission rate by aggregating data across both bands, licensed and unlicensed.
- *Carrier Selection (CS).* The main feature of CS functionality is to identify a 20MHz channel experiencing the lowest interference levels. Frequency selection is performed by calculating the average received interference power for each of the candidate carriers. Since traffic as well as the number of nodes may vary, CS is performed periodically.
- *Discontinuous Transmission (DTX).* DTX is a standardized LTE mechanism disabling the radio transceiver in the connected mode to enter the energy saving regime and thus reduce interference at the air interface. There are two DTX cycles that can be set at the user equipment (UE), long and short. Transitions between them are triggered directly by the base station. The former

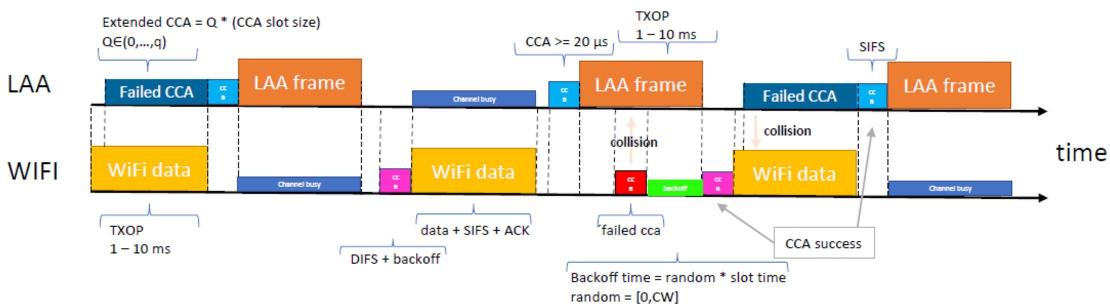


FIGURE 2. LBT-based channel sharing mechanism of LAA.

is utilized during UE's inactivity periods, when it only needs to check the control channels and no resources are assigned. This mode is to be used by LAA to disable UE's activity during Wi-Fi transmissions.

B. LBT-BASED FUNCTIONALITY OF LAA

The LBT channel sharing method that senses the medium before transmitting has been proposed for the LAA system. Among various LBT options, 3GPP – given the consent of all the involved stakeholders – has selected LBT category 4 as the baseline mechanism. This category is represented by an agile architecture similar to that already used for the coexistence with Wi-Fi nodes. After their preliminary analysis, 3GPP continued work on LAA by defining the downlink operation in Release 13 and the uplink operation in Release 14.

As shown in Fig. 2, before initiating a transmission, LBT performs clear channel assessment (CCA) for checking on the channel status. If during the CCA a device or BS detects an energy level below the CCA threshold, then the medium is assumed free and it is possible to transmit for a period of time equal to the Channel Occupancy Time (COT). The CCA threshold configuration is crucial for the LAA system operation. An increase of this threshold leads to a reduction in the sensing area around the BS (eNodeB) with weaker performance similar to the case without LBT. On the other hand, a significant reduction of the threshold may not improve the performance either, as the eNodeB coverage area becomes wider, hence increasing the probability of intercepting another signal and thus reducing the probability of transmission. If during the CCA the medium is sensed busy, an extended CCA (ECCA) is invoked until it is free. This mechanism monitors the channel for random N multiples of the CCA time, where N is the number of clear idle slots that must be observed before initiating a transmission.

Even though LBT is similar to carrier sensing in Wi-Fi, there are several important differences: (i) Wi-Fi does not implement any defer periods, and (ii) no exponential backoff of the contention window is performed by LBT. Once it is confirmed that the channel is free, data is transmitted from the eNodeB to the UE. According to ETSI specifications, there are restrictions on Radio Local Area Network (RLAN) operation. For the equipment used in 5GHz spectrum, there are two different types defined: frame base equipment (FBE) and load base equipment (LBE). Here, FBE utilizes fixed frame periods (FFP), where after the channel is sensed free the device transmits immediately. LBE is demand-driven, wherein the device can transmit on the channel as long as it has data in its buffer.

While at the first glance FBE might appear to be the preferred solution as it suits the LTE subframe/frame based approach better, there are several issues associated with this method. The transmission opportunity is limited because of the channel contention constraints of FBE. As a consequence, this might involve higher service delays. Moreover, synchronization issues might emerge when multiple LAA cells sense the channel free with the result that one or more LAA cells collide. Unlike in FBE, the demand-centric behavior of LBE guarantees higher flexibility in terms of the channel access. This approach is also more closely similar to CSMA/CA of Wi-Fi, thus promising better and simpler coexistence mechanisms for Wi-Fi and LAA.

III. PROPOSED CHANNEL SHARING MECHANISM

In this paper, we propose a new channel sharing mechanism for LTE/Wi-Fi coexistence on the same channel in the ISM bands. The aim of the proposed design is to enable: (i) fairness of resource division between active sessions across all the systems utilizing the channel of interest, and (ii) QoS guarantees of the LAA sessions in terms of both throughput and upper delay bound.[1] Our design is based on the assumption that the LAA system continuously monitors the process of data transmission over the air interface, including those periods when the LAA BS is inactive. The two basic principles instrumental to achieving the claimed functionality are: (i) adaptive duty cycle, and (ii) LAA CAC (connection admission control). In this section, we first introduce the system model and our key assumptions. Next, we describe the functionality of the proposed system in detail. An extension to the case of general environment with multiple LAA BSs is finally given below.

[1] Since LTE scheduling is vendor-specific, we do not incorporate its details into the proposed mechanism and thus concentrate on an upper bound for the delay.

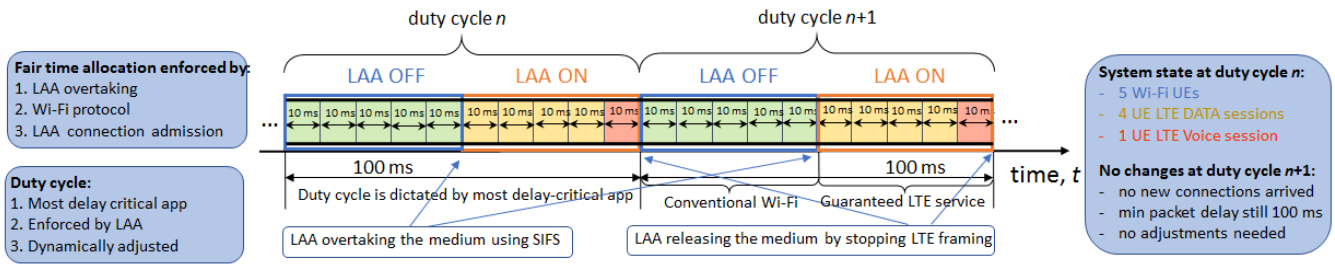


FIGURE 3. Resource allocation in the proposed LAA channel sharing mechanism.

A. SYSTEM MODEL AND ASSUMPTIONS

We consider one Wi-Fi AP and one LAA BS that are located in the same geographical area. These Wi-Fi AP and LAA BS may not be co-located, that is, no information needs to be exchanged between the Wi-Fi AP and the LAA BS prior to or during the operation. The system is dynamic thus implying that sessions arrive and depart to/from Wi-Fi AP and LAA BS. For simplicity of exposition, we assume that two types of sessions arrive to the LAA BS. These are non-real-time best-effort sessions having no QoS requirements and real-time sessions having specified throughput and delay requirements. Only the best-effort traffic sessions are assumed to arrive to the Wi-Fi AP. No additional requirements are imposed on the traffic characteristics. Note that the system in question can be extended to a larger number of traffic classes with different QoS requirements. The assumption of only one QoS class is relaxed further in Section V.

We also assume that the LAA BS is capable of hearing transmissions of all active Wi-Fi stations. During its operation, the LAA BS keeps track of the number of active Wi-Fi stations. This is done by eavesdropping on the Wi-Fi packets and e.g., storing their unique MAC addresses. Since the sessions arrive and depart dynamically, each time an address is stored a timer is started. This timer is renewed every time when a packet with this address is captured again. Finally, we assume that during the time allocated to the LAA BS, regular LTE operation is performed.

B. BASIC OPERATIONAL PRINCIPLES

Having a number of active Wi-Fi sessions at each instant of time is important for the proposed channel sharing mechanism. The Wi-Fi-related information is required to provide fairness of resource division and QoS guarantees to the LAA sessions. The fairness of resource division between all the active sessions that share the medium is enforced by the *LAA CAC algorithm* that rejects LAA sessions that may violate it. At the same time, LAA CAC ensures the QoS guarantees in terms of session throughput for the real-time sessions. The QoS guarantees in terms of upper delay bound are further provided by the *adaptive duty cycle algorithm*.

More specifically, Fig. 3 illustrates the typical state of the proposed channel organization procedure by showing

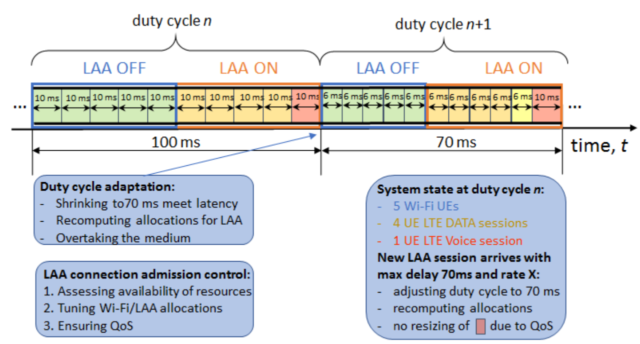


FIGURE 4. Operation of the proposed LAA CAC algorithm.

two duty cycles, n and $n + 1$. To reduce the implementation complexity, the resources in our LAA system are divided in time between the Wi-Fi AP and the LAA BS. The LAA BS fully controls the resource allocation between the Wi-Fi APs and itself, thus preventing the Wi-Fi stations from competing at any instant of time by utilizing short inter-frame space (SIFS) interval and enforcing LTE framing. During this time, the LAA BS follows the framing structure of the conventional LTE by allocating resources to the LAA sessions in terms of the resource blocks across frequency and time. When the time allocation for LTE expires, the LTE framing is ceased and the medium is released for the Wi-Fi stations that continue to compete for radio resources according to the IEEE 802.11 MAC protocol.

The current duty cycle duration is determined by the session with the strictest delay requirements (e.g., voice session in Fig. 3 with the maximum allowed delay of 100ms). The remaining time allocations are divided fairly between all of the sessions. This has been ensured in the past by accepting not more than a certain number of LAA sessions. For simplicity, in Fig. 3, all of the sessions are assumed to require the same throughput. Hence, they receive exactly the same time allocation in 100ms duty cycle, and the system supports 5 Wi-Fi and 5 LAA sessions. The CAC algorithm implemented in the LAA BS is split into two logical parts: (i) resource management for accepting/rejecting an LAA session, and (ii) reallocation of radio resources for arriving/departing sessions. Below we consider these two phases in more detail.

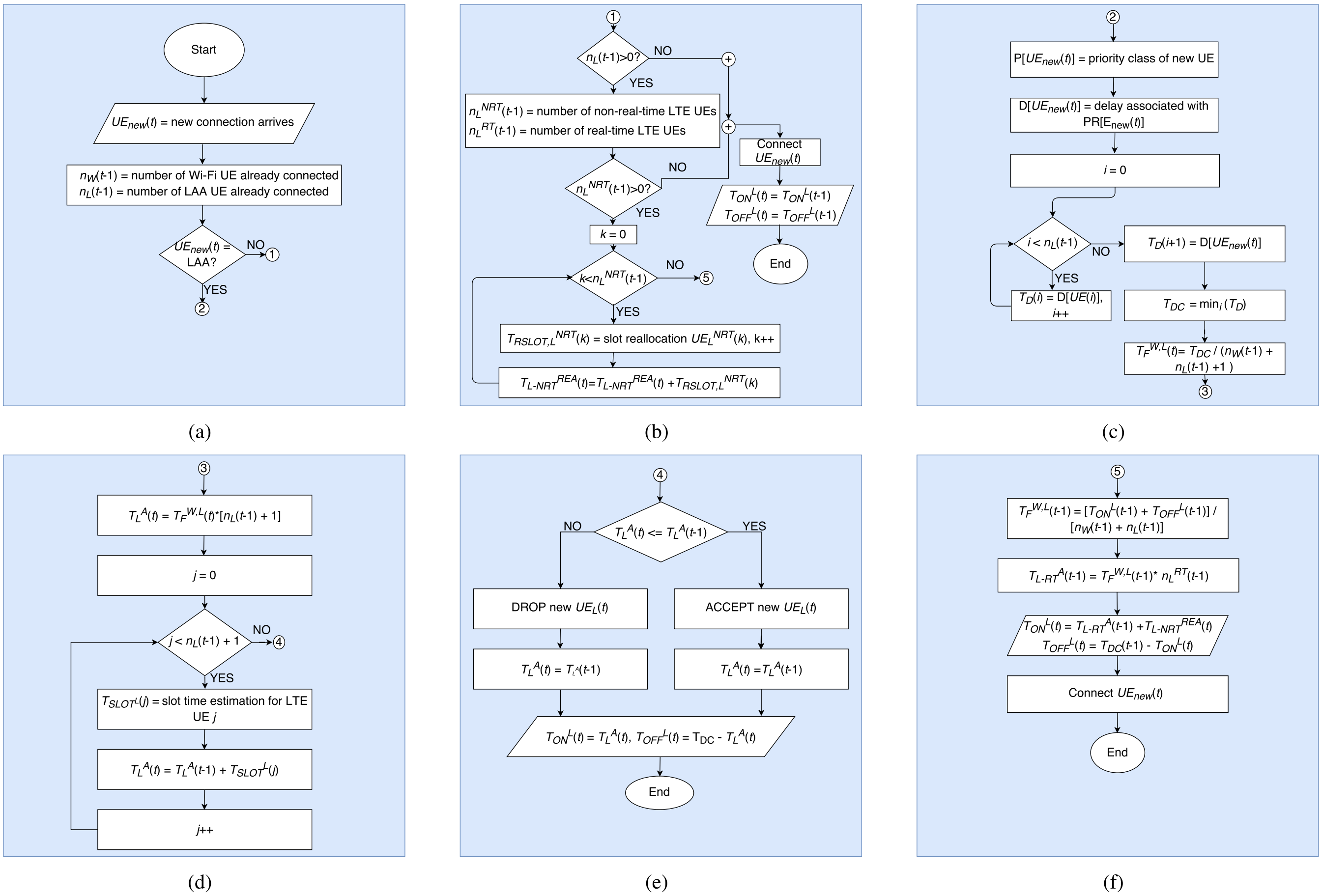


FIGURE 5. Flow-chart diagrams: handling an arriving LAA session.

C. LAA CONNECTION ADMISSION CONTROL

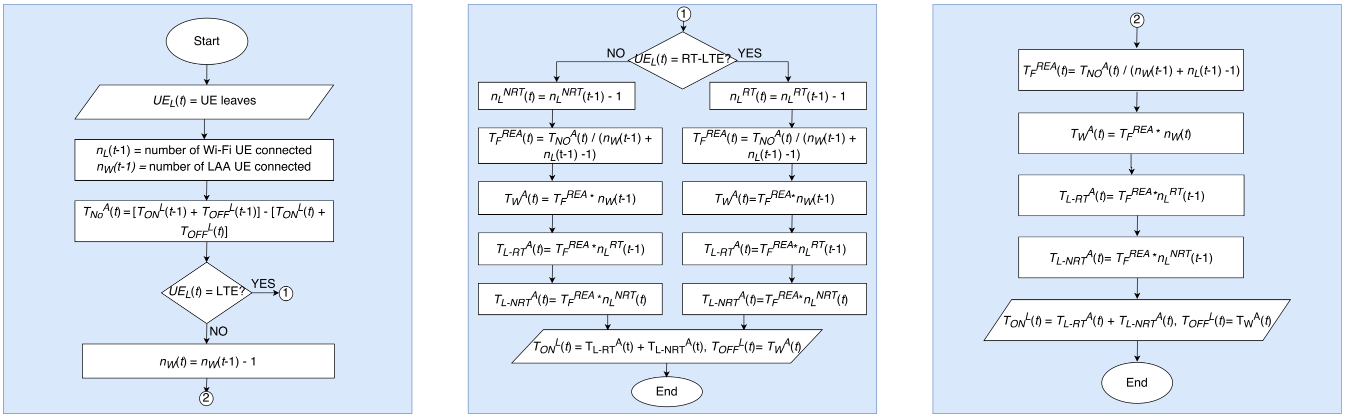
To illustrate the intended operational dynamics, consider a new session with stricter delay requirements that arrives during the duty cycle n. A decision on the acceptance of rejection of this session is made by the LAA CAC system that first checks whether the resource allocation of the Wi-Fi session is going to remain fair after the acceptance of this new session. This is done by reducing the duty cycle duration to 70ms, reserving the required amount of time for the QoS sessions, and recomputing all the allocations for the rest of the best-effort sessions in the system. If there is a fair division of resources, the new session is accepted and the duration of the next duty cycle is reduced to 70ms as shown in Fig. 4. If such a configuration is not feasible, i.e., fairness is likely to be violated by this session, it is then rejected. The flow-chart diagrams that show handling of the arriving LAA session are provided in Fig. 5.

Consider now an LAA session that leaves the system. The time slot that was previously assigned to thus leaving session is now split equally between the Wi-Fi and the best-effort LAA users by following the procedure in Fig. 6. This procedure minimizes the waste of radio resources as the system does not wait for the new session arrival to update the channel sharing parameters.

There are other events that may or may not trigger the resource reallocation process at the LAA BS. Particularly, the arrival of a new Wi-Fi session only triggers resource reallocation when the available resources can be reallocated such that the throughput requirements of the QoS-sensitive sessions are presumed. If not, no action is taken and the unfair allocation for the Wi-Fi sessions continues until the departure of one or more LAA sessions. This behavior is unavoidable when no explicit control over the Wi-Fi APs is available. Further, upon the departure of a Wi-Fi session, the LAA system reallocates the resources for the rest of the sessions. This is needed to ensure that the best-effort LAA sessions enjoy equal division of the resources. The corresponding process is demonstrated in Fig. 6. Note that the arrivals and departures of the Wi-Fi sessions are detected at the LAA BS by monitoring the shared channel environment as explained above.

IV. PERFORMANCE EVALUATION MODEL

Simulation studies of channel access protocols are typically performed using extensive computer modeling tools. However, to understand the basic trade-offs between the involved system parameters and performance metrics of a protocol, especially at its design phase, simpler mathematical models



(a) (b) (c)

FIGURE 6. Flow-chart diagrams: handling a departing LAA session.

TABLE 1. Notations used in this work.

Parameter	Definition
R	Raw data rate of radio technology
λ	Arrival intensity of sessions
q_W	A fraction of Wi-Fi sessions
$q_L = 1 - q_W$	A fraction of LTE sessions
$\vec{\pi}$	Steady-state distribution vector $\vec{\pi}$
r_L	Session data rate of LTE service
t_L	Upper delay bound of LTE service
T_A	Current resource allocation time
T_M	Maximum resource allocation time
N_M	Maximum number of LTE sessions
$S_W(t)$	Number of Wi-Fi sessions at time t
$S_L(t)$	Number of LTE sessions at time t
$S(t)$	State space of the model
$1/\mu_W$	Mean session duration of Wi-Fi session
$1/\mu_L$	Mean session duration of LTE session
$p_{i,j}$	Transition rates between states of the model
ρ_W	Offered traffic load to Wi-Fi
ρ_L	Offered traffic load to LTE
p_L	LTE session loss probability
$E[N_W], E[N_L]$	Mean number of Wi-Fi/LTE sessions
$E[R_W]$	Mean data rate of Wi-Fi session
$R_i(j)$	Mean data rate of Wi-Fi session when state is i, j
$R_{L,1}$	Rate required by a single LTE session
γ	Fraction of resource division between Wi-Fi/LTE
f_V	Fraction of time when QoS violation may occur
$q_{(i,j),(l,k)}$	Transition rates of $\{S_W(t), S_L(t), t > 0\}$
Q	Infinitesimal generator of $\{S_W(t), S_L(t), t > 0\}$
$p_{i,j}$	Steady-state probability of i Wi-Fi and j LTE sessions
$\vec{p}$	Steady-state probability vector

are often preferred. In this section, we formulate our model of the proposed channel sharing mechanism and then derive the basic performance metrics of interest. The considered parameters include the LAA session loss probability, the number of Wi-Fi and LAA sessions in the system, the fraction of data rate division between Wi-Fi and LAA, as well as the data rate achieved by a single Wi-Fi session. Finally, we extend the constructed model to capture imperfections of system operation – to estimate the fraction of time when QoS degradation might be experienced. The notations used in this section are summarized in Table 1.

A. OUR PROPOSED MODEL

Let new session arrivals to the LAA system follow a homogeneous Poisson process with the intensity of λ. We assume that an arbitrary arriving session is of the LAA type with probability q_L. With the complementary probability $q_W = 1 - q_L$, a session arrives to the Wi-Fi AP. Each LAA BS supports standard LTE service classes. Every LTE class i is characterized by the required data rate and delay bound, (r_i, t_i). The probability that an LAA session belongs to class i is q_i. As Wi-Fi is not assumed to differentiate between the service classes, only one type of data sessions arrives to the Wi-Fi AP. The standard 3GPP full-buffer traffic model is assumed for the data sessions, that is, data source always has data to transmit and a single session may fully occupy the channel [30]–[32]. The session durations are all exponentially distributed with the rate of μ_W and μ_i for the Wi-Fi and LTE class i, respectively.

Recall that the proposed channel sharing mechanism divides the air time (not the actual data rate) between the stations equally. To keep the model feasible, we assume that the transmit power control mechanisms of LTE as well as the adaptive modulation and coding schemes of Wi-Fi and LTE maintain the link quality at the acceptable levels at all times. Introducing the specifics of random node deployment is not expected to yield fundamentally different trade-offs. This is particularly true considering that the conventional coverage areas of Wi-Fi APs and micro/pico LTE BSs are limited to several tens of meters. Hence, we assume that the raw data rate of the channel is R, measured in bits per second.

The service process of sessions in the LAA deployment can be modeled by using a multi-dimensional, continuous-time Markov chain. Specifically, assuming N LTE service classes, the number of dimensions is $N + 1$, which quickly leads to the state explosion problem. The reason is that different session types in the system enforce new durations of the duty cycle. Therefore, in what follows we consider a single type of the LAA sessions, with the rate requirement of r_L, the upper bound on delay t_L, and the service rate of μ_L.

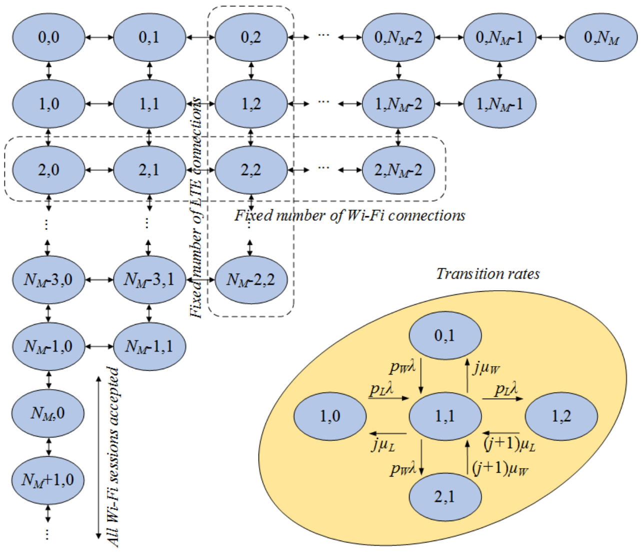


FIGURE 7. State transition diagram of $\{S_W(t), S_L(t), t > 0\}$.

Consider the continuous-time two-dimensional stochastic process $\{S_W(t), S_L(t), t > 0\}$, where $S_W(t)$ and $S_L(t)$ denote the numbers of active Wi-Fi and LTE sessions in the LAA system at time t, respectively. Due to the Poisson nature of arrival and service processes, we observe that it is Markov in nature. As all of the sessions arriving to Wi-Fi are accepted for service, the state space of $S_W(t)$ is $\in \{0, 1, \dots\}$. The state space of the LTE part depends on the current state of the Wi-Fi part and constitutes

$$S_L(t) = \left\{0, 1, \dots, \left\lfloor \frac{r_L}{R} \right\rfloor - S_W(t)\right\}, \tag{1}$$

where $S_W(t)$ is the current number of active Wi-Fi sessions and $\lfloor r_L/R \rfloor$ is the maximum number of LTE sessions in the system. It is important to note that the common state space is not a direct product of two subsets $S_W(t)$ and $S_L(t)$. Letting $N_M = \lfloor r_L/R \rfloor$, the overall state space, $S(t)$, is illustrated in Fig. 7 by clarifying the state-transition diagram of $\{S_W(t), S_L(t), t > 0\}$.

The data rates of the model forming the infinitesimal generator, Q, can now be established. Recalling that we accept all the incoming Wi-Fi sessions and the service rates of Wi-Fi and LTE are μ_W and μ_L, respectively, for an arbitrarily chosen state $(i, j) \in S$ we have

$$\begin{cases} q_{(i,j),(i+1,j)} = q_W\lambda, \\ q_{(i,j),(i-1,j)} = i\mu_W, \\ q_{(i,j),(i,j+1)} = q_L\lambda, \\ q_{(i,j),(i,j-1)} = j\mu_L, \end{cases} \tag{2}$$

thus supplementing the state transition diagram in Fig. 7.

As one may observe, there is only one class of states in the modeled Markov chain, which is irreducible and aperiodic. Hence, the resulting process is ergodic, where the final probabilities coincide with the stationary state probabilities collected as the vector $\vec{p}$ [33], i.e.,

$$p_{i,j} = \lim_{t\to\infty} p_{i,j}(t), \quad \{i, j\} \in S. \tag{3}$$

To determine $\vec{p}$, consider the local balance equations that are satisfied for ergodic Markov chains, see Fig. 7,

$$\begin{cases} p_{i,j}i\mu_W = p_{i-1,j}p_W\lambda, \\ p_{i,j}j\mu_L = p_{i,j-1}p_L. \end{cases} \tag{4}$$

Using the first equation in (4), we obtain

$$\begin{aligned} p_{i,j} &= p_{i-1,j}\frac{p_W\lambda}{i\mu_W} = p_{i-1,j}\frac{p_W\rho}{i} = \\ &= p_{i-2,j}\frac{(p_W\rho)^2}{i(i-1)} = \dots = \\ &= p_{0,j}\frac{(p_W\rho)^i}{i!}, \end{aligned} \tag{5}$$

where $\rho_W = \lambda/\mu_W$ is the offered traffic load onto Wi-Fi.

Utilizing the second balance equation, we establish

$$\begin{aligned} p_{0,j} &= p_{0,j-1}\frac{p_L\lambda}{j\mu_L} = p_{0,j-1}\frac{p_L\rho_L}{j} = \\ &= p_{0,j-2}\frac{(p_L\rho_L)^2}{j(j-1)} = \dots \\ &= p_{0,0}\frac{(p_L\rho_L)^j}{j!}, \end{aligned} \tag{6}$$

where $\rho_L = \lambda/\mu_L$ is the offered traffic load onto LTE.

Substituting (6) into (5) and then back to (4), we arrive at

$$p_{i,j} = p_{0,0}\frac{(p_L\rho_L)^j}{j!}\frac{(p_W\rho_W)^j}{i!}, \tag{7}$$

where $p_{0,0}$ is the only unknown.

Exploiting the normalization condition, $p_{0,0}$ is expressed as

$$p_{0,0} = G^{-1}(S) = \left(\sum_{\forall(i,j)\in S}\frac{(p_L\rho_L)^j}{j!}\frac{(p_W\rho_W)^j}{i!}\right)^{-1}, \tag{8}$$

where S is the overall state space.

The above expression for $p_{0,0}$ is not convenient for calculations. However, benefiting from the specifics of the state space S, we may rewrite it as

$$p_{0,0} = \left(\sum_{i=1}^{\infty}\sum_{j=1}^{N_M-i}\frac{(p_L\rho_L)^j}{j!}\frac{(p_W\rho_W)^j}{i!}\right)^{-1}. \tag{9}$$

B. PERFORMANCE METRICS

Based on the previous considerations, the probability of the LTE session loss can be expressed as

$$p_L = \sum_{\forall(i)\in(i,j):j=N_M-i} p_{i,j}. \tag{10}$$

Further, the numbers of Wi-Fi and LTE sessions are

$$E[N_W] = \sum_{\forall i\in S} ip_{i,j},\ E[N_L] = \sum_{\forall j\in S} ip_{i,j}. \tag{11}$$

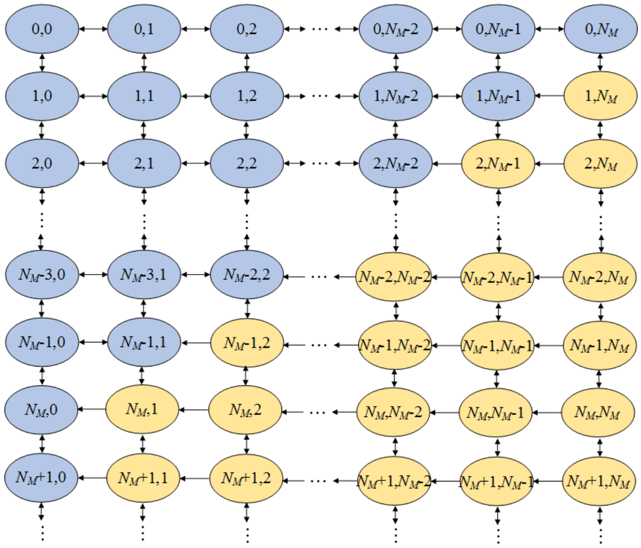


FIGURE 8. State transition diagram of $\{S_W^\star(t), S_L^\star(t), t > 0\}$.

Recall that in the proposed system the required rate for LTE sessions is always delivered. However, as we accept all of the Wi-Fi sessions, the mean data rate of the Wi-Fi sessions is given by

$$E[R_W] = \sum_{\forall i \in S: i \neq 0} p_{i,j} R_i(j), \tag{12}$$

where $R_i(j)$ is the mean data rate of a Wi-Fi session when there are i and j Wi-Fi and LTE sessions in the LAA system. We thus have

$$R_i(j) = \frac{R - jR_{L,1}}{i}, \quad i = 1, 2, \ldots, \; j = 1, 2, \ldots, \tag{13}$$

where $R_{L,1}$ is the data rate required by a single LTE session.

C. ANALYSIS OF IMPERFECTIONS

The inherent lack of control over acceptance of Wi-Fi sessions as well as imperfect estimation of the number of ongoing Wi-Fi connections may induce performance degradation for LTE sessions. To account for this possible degradation, we modify the state transition diagram of the process that models the number of Wi-Fi and LTE sessions in the LAA system as shown in Fig. 8. As one may observe, even if the system is fully loaded in states $(i, N_M - i)$, $i = 0, 1, \ldots, N_M$, there could still be arrivals of Wi-Fi sessions that are accepted by default. The complete state space of the system at time t, $S(t)$, is then characterized by the direct product of $S_W^\star(t) \in \{0, 1, \ldots, \}$ and $S_L^\star(t) \in \{0, 1, \ldots, N_M\}$. The transition rates for the new states are given by

$$\begin{cases} q_{(i,j),(i+1,j)} = q_W \lambda, \\ q_{(i,j),(i-1,j)} = i\mu_W, \\ q_{(i,j),(i,j+1)} = 0, \\ q_{(i,j),(i,j-1)} = j\mu_L. \end{cases} \tag{14}$$

The new process $\{S_W^\star(t), S_L^\star(t), t > 0\}$ remains Markov and ergodic. However, due to the complex structure of the state transition diagram, there is no analytical solution for its steady-state probabilities. To solve the system at hand, we employ the finite Markov chain approximation [34], [35] by limiting the number of Wi-Fi sessions to a finite but rather large value. The steady-state probability vector $\vec{p}^\star$ is then obtained as the direct solution to the system of linear equations that describe the behavior of the chain in equilibrium.

Let f_V be the fraction of time spent in the set of states, where QoS guarantees provided to the LTE sessions can be violated. Once $\vec{p}^\star$ is obtained, we have

$$f_V = \sum_{i=1}^{\infty} \sum_{j=\max(N_M - i + 1, 1)}^{N_M} \pi_{i,j}^\star. \tag{15}$$

Utilizing the theory of absorbing Markov chains and, in particular, introducing the fundamental matrix, one could obtain advanced metrics that pertain to the imperfections of the proposed channel sharing mechanism [36]. These include the mean and the distribution of time to reach the set of states, where the QoS may be violated, as well as the mean and the distribution of time to leave this set. However, as we will see in what follows, p_V is small for the reasonable values of offered traffic load for both Wi-Fi and LTE sessions.

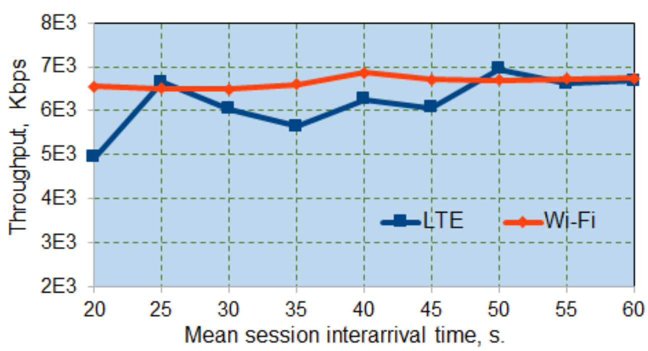
V. PERFORMANCE ASSESSMENT CAMPAIGN

In this section, we conduct an extensive numerical assessment of the proposed channel sharing mechanism. We start by addressing the fairness of rate division between LTE and Wi-Fi sessions. Then, we proceed with investigating the QoS performance of LTE sessions by highlighting the importance of two main features in the proposed mechanism: adaptive duty cycle and LAA CAC. We continue with comparing the developed protocol against an LBT-based LAA implementation. Finally, we use our analytical model to characterize the QoS violation regime of the system caused by the lack of control over the acceptance of Wi-Fi sessions.

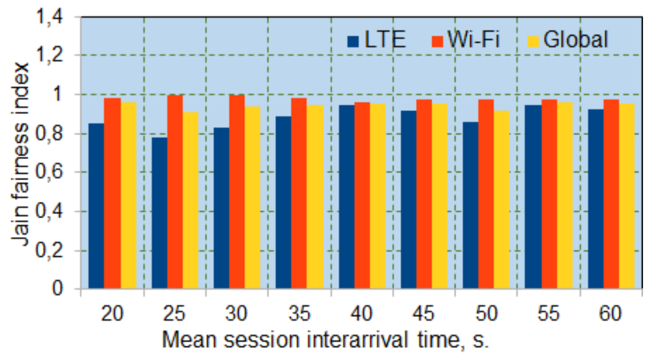
A. SIMULATION SETUP AND PARAMETERS

To assess fairness and QoS performance, we implemented the proposed channel sharing mechanism in the ns3 simulation environment. Here, LAA is modeled as a supplemental downlink in the 5GHz ISM band, with the primary cell (PCell) always operating in the licensed band. The target scenario has the same features as the indoor 3GPP model in the rectangular deployment area of 120m by 50m, where the Wi-Fi AP and the LAA BS are placed in the geometrical center.

The parameters used in our simulations are summarized in Table 2. The arrival structure of sessions is assumed to follow a Poisson process with the intensity of λ. If admitted to the system, their source remains stationary at the same location until the end of its service time. An individual arrival is classified as an LTE session with the probability of p_L and as a Wi-Fi session with the complementary probability $1 - p_L$. To highlight the QoS performance of the proposed



(a)



(b)

FIGURE 9. Fairness and QoS assessment of the proposed channel sharing mechanism for the data application. (a) Throughput. (b) Jain's fairness index.

TABLE 2. Parameters utilized in simulations.

Parameter	Value
Mean session duration	2min
Network layout	Indoor scenario
System bandwidth	20MHz
Carrier frequency	5GHz
LTE packet scheduler	Priority set scheduler (PSS)
Base station Tx power	18dBm
UE Tx power	18dBm
Path loss model	IEEE 802.11ax indoor model
Antenna pattern	2D omni-directional
Simulation time	200min

TABLE 3. Application traffic characterization.

Application	Data rate	Delay	Inter-packet time	Packet size
Gaming	80Kbps	50ms	5ms	50 bytes
Video	1Mbps	150ms	4ms	500 bytes
Voice	80Kbps	100ms	10ms	100 bytes
Data	5Mbps	300ms	2ms	1500 bytes

LAA system, in several tests we utilized complex traffic composition. Particularly, we assumed four application classes with different traffic requirements as specified in Table 3. Accordingly, each LTE session is mapped onto an application class with the corresponding probabilities, p_G, p_D, p_{Vo}, and p_{Vi}, such that $p_G + p_D + p_{Vo} + p_{Vi} = 1$.

In the ns3 environment, the statistics is conventionally collected by employing the built-in FlowMonitor tool, which tracks the per-flow metrics at the IP layer. To be able to monitor the packet-level metrics, such as delay and probability that the delay exceeds a certain upper bound, we developed our own tool that collects statistics associated with individual packets at the MAC layer.

B. FAIRNESS AND QoS PERFORMANCE

Let us first concentrate on analyzing the fairness of resource allocation, including intra- and cross-technology fairness. We thus assess the fairness of resource division between the sessions by using the well-known Jain's fairness index as defined in [37]

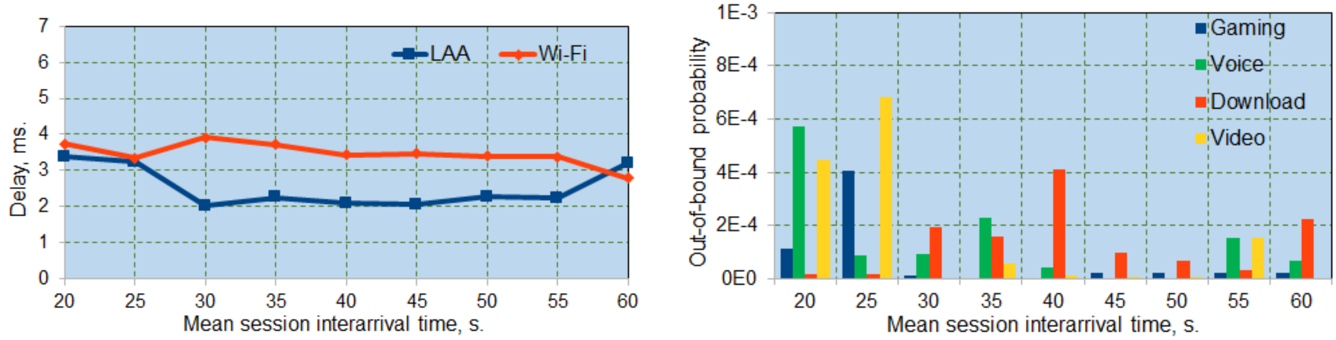
$$J = \left(\sum_{i=1}^{n} x_i\right)^2 \frac{1}{n\sum_{i=1}^{n} x_i^2}, \tag{16}$$

where n is the number of users and x_i is the data rate of i-th user. Observe that $J(n) \in (0, 1)$, where the higher the value of the index is, the better the fairness of the resource allocation across sessions becomes.

To assess the fairness of resource allocation, we assume that all of the sessions arriving to the LAA BS are data sessions, that is, $p_D = 1$. The fraction of the LTE sessions is $p_L = 0.5$. Hence, Fig. 9 illustrates the performance measures of interest as a function of the average session interarrival time. Recalling that the average session duration is set to 60s, the offered traffic load, ρ, varies from 3 to 1, that is, the system always resides in overloaded conditions. The overall simulation time is set to 200min. The exponentially-weighted moving average test with a smoothing exponent of $\gamma = 0.05$ is used to determine the end of the warm-up period. The average warm-up period is thus observed to be 1.56min, and no statistics is collected during it.

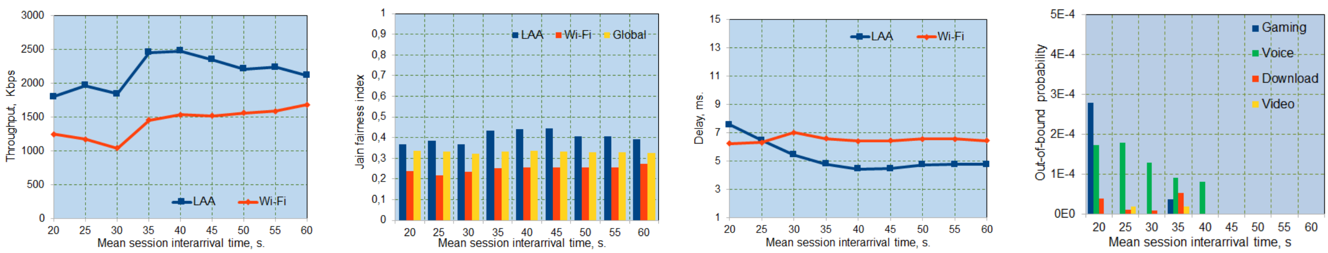
Analyzing the data presented in Fig. 9, one may conclude that for all the values of session inter-arrival time the throughput levels achieved by Wi-Fi and LTE are similar, hence implying that the proposed channel sharing mechanism satisfies the main requirement of the LAA system. This is also confirmed by Fig. 9(b), where Jain's fairness index is shown for LTE and Wi-Fi sessions as well as globally across the two technologies. We learn that for both Wi-Fi and LTE sessions the Jain's fairness index is always greater than 0.8, which is the indicator of an extremely fair system [37].

One of the attractive features enabled by the proposed channel sharing mechanism is that in addition to fairness of resource allocation it provides performance guarantees for the LTE sessions. Let us now consider the case where $p_G = p_D = p_{Vo} = p_{Vi} = 0.25$, thus implying that an arrival to the LAA BS is classified as gaming, data, voice, or video session with equal probabilities. Since throughput guarantees are delivered by design while no fairness criteria can be applied to mixed traffic conditions, we proceed with analyzing the mean upper bound of delay and out-of-bound probability as illustrated in Fig. 10. Recall that according to the proposed channel sharing mechanism an arrival of a session with stricter delay requirements leads to a decrease



(a) (b)

FIGURE 10. **QoS assessment of the proposed channel sharing mechanism for the mixture of applications. (a) Upper delay bound. (b) Out-of-bound probability.**



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

FIGURE 11. **Fairness and QoS assessment when all the LTE sessions are accepted. (a) Throughput. (b) Jain's fairness index. (c) Upper delay bound. (d) Out-of-bound probability.**

in the duty cycle – by attempting to satisfy the requirements of this new session. Hence, in the presence of at least one gaming application, the requirements for data, voice, and video sessions are satisfied by design. As one may observe in Fig. 10(a), the mean upper delay bound for the LAA and Wi-Fi sessions is perfectly below 5ms for all the values of the mean inter-arrival time.

Note that the mean upper delay bound values do not necessarily deliver the full picture of the delay dynamics. Since one of the purposes of the proposed scheme is to offer performance guarantees to the LTE sessions, we now proceed by addressing the probability that the delay experienced by a packet is higher than a certain target value, named the out-of-bound probability, which is illustrated in Fig. 10(b). As one may notice, the out-of-bound probability for all types of sessions is always under 0.001 even for the shortest mean inter-arrival time of 20s, thus corresponding to the offered traffic load of $\rho = 3$.

C. COMPARISON WITH EXISTING APPROACHES

A critical requirement for the LTE/Wi-Fi coexistence is that the LAA BS does not interfere with the existing Wi-Fi APs more than another Wi-Fi AP operating on the same channel would. We demonstrated that this important consideration is satisfied for the proposed LAA system design. In this subsection, we compare the performance of the proposed channel sharing mechanism against that of the LBT-based access method from [38] and that of the scheduling-based access with fixed Wi-Fi and LTE allocations. The latter resembles in principle the approach of [19], while our performed comparison is aimed to emphasize the importance of the two main algorithms proposed as part of the channel sharing mechanism, namely, adaptive duty cycle and LAA CAC.

To compare the proposed mechanism with the conventional scheduling-based approach, consider first the case of homogeneous LTE traffic with $p_D = 1$ and assume that no LAA CAC is performed, that is, all the LTE session arrivals are accepted by the system. Analyzing the performance of this setup in Fig. 11 and recalling that the proposed channel sharing mechanism reserves radio resources for all the LTE sessions by default, one may conclude that, on average, more resources are provided to the LTE sessions than to the Wi-Fi sessions. The reason is that all of the LTE sessions are admitted and less throughput is made available to the Wi-Fi sessions. Furthermore, as the fairness among LTE and Wi-Fi sessions is preserved, the global cross-technology fairness is compromised severely, see Fig. 11(b). Understanding the data presented in Fig. 11(c), we see that the mean upper delay bound is still kept at acceptable levels. The out-of-bound probabilities, however, are much higher as compared to the proposed channel sharing mechanism, especially for the Wi-Fi sessions. Hence, the LAA CAC algorithm affects the performance of Wi-Fi sessions. Our presented analysis maintains that the said LAA CAC algorithm is crucial for

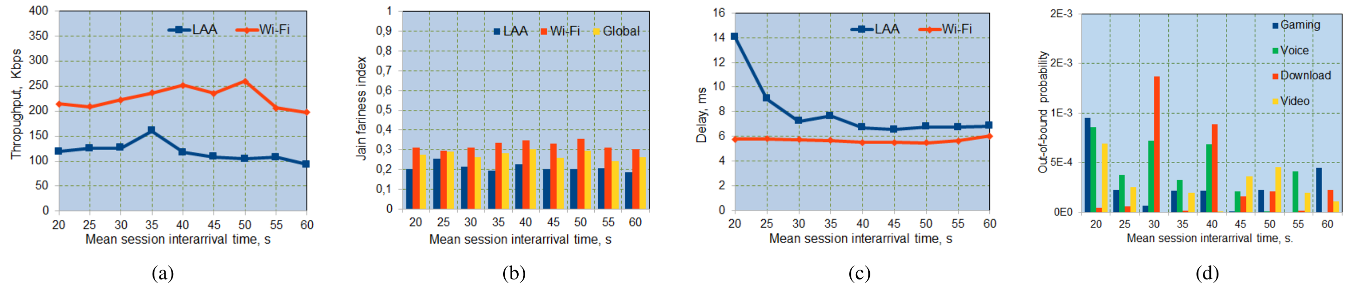


FIGURE 12. Fairness and QoS assessment when the duty cycle is fixed. (a) Throughput. (b) Jain's fairness index. (c) Upper delay bound. (d) Out-of-bound probability.

satisfying the main coexistence requirement for a fair division of resources between Wi-Fi and LTE.

To demonstrate the effects of adaptive duty cycle, consider the system with $p_G = p_D = p_{Vo} = p_{Vo} = 0.35$. To this end, Fig. 12 illustrates the system performance with the LAA CAC enabled when the duty cycle is fixed to 300ms. First, observe that in heterogeneous traffic conditions the division of throughput between the sessions is not fair. The reason is that LTE serves mixed traffic of various applications whereas Wi-Fi only handles data sessions. This behavior is also reflected in Fig. 12(b), which shows intra- and cross-technology Jain's fairness index. It is interesting to note that even though the mean upper delay bound is approximately two times higher than that with adaptive duty cycle enabled, see Fig. 10(a), it is still maintained at acceptable levels, see Fig. 12(c). The explanation roots in the presence of the LAA CAC algorithm that prevents from entering overloaded conditions. However, the out-of-bound probability is substantially higher for all the considered values of the mean session inter-arrival time, as compared to the system with the adaptive duty cycle, see Fig. 10(b) and Fig. 10(b). This is because the duty cycle remains constant and is set to a relatively large value of 300ms.

Observe that by disabling either the adaptive duty cycle or the LAA CAC scheme our system does not compromise the proposed channel sharing mechanism completely. More specifically, when LAA CAC is off, no fair division of resources is achieved but the adaptive duty cycle algorithm still ensures acceptable performance for the QoS-sensitive LTE sessions. When the former scheme is disabled instead, fairness can be maintained in homogeneous traffic conditions, but QoS metrics of the LTE sessions can then be violated. Enabling the two algorithms simultaneously allows for preserving both QoS and fairness.

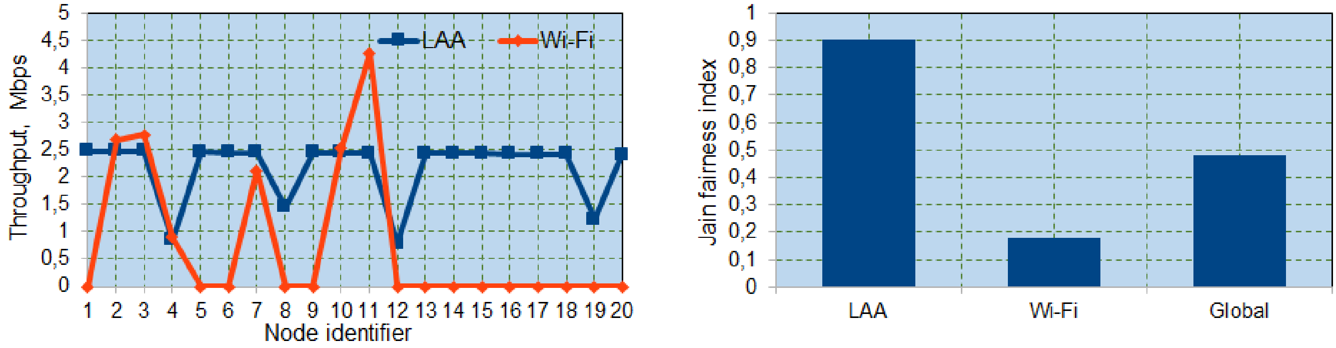
Following the guidelines in [38] and utilizing the source code provided, we further implemented the simulation scenario for the LBT-based LAA system. Note that the corresponding simulation setup is slightly different from the one that we employed for the proposed LAA system analysis. Particularly, no session dynamics is presumed therein. Instead, the numbers of sessions are set to fixed values of 20 for LTE and 20 for Wi-Fi, which are initialized at the beginning of simulation. Full-buffer traffic model is still assumed for both LTE and Wi-Fi technologies. The rest of the parameters remain the same as in Table 2.

First, observe that LBT-based LAA channel sharing cannot guarantee the required delay bounds by design. Along these lines, Fig. 13 reports on the throughput and fairness levels in the LBT-based LAA system. As one may observe, the LBT mechanism is clearly biased towards LTE sessions by providing, on average, much higher throughput to them. Some of the Wi-Fi sessions receive no throughput at all, while some other perform on a par with LTE sessions. It is also interesting to notice that the system is almost perfectly fair with respect to the LTE sessions as illustrated in Fig. 13(b). This is in high contrast with the proposed LAA channel sharing mechanism, where near-perfect intra- and cross-technology fairness is observed, see Fig. 9.

Further, we note that unfairness of the LBT-based system may very well be related to the choice of the LBT parameters. Different from the proposed channel sharing mechanism, LBT-based design requires additional configuration and possibly calls for dynamic adaptation during its operation. Even though there might be a set of parameters ensuring fair allocation of resources for LBT-based design, the need for on-the-fly adaptation of the system parameters may complicate its efficient implementation, see [23]. Second, the LBT procedure as specified by 3GPP is fundamentally different from the CSMA/CA protocol in IEEE 802.11 systems by implying that it may not be trivial to identify the parameters that ensure fairness of resource allocation [24]. The performance illustrated in Fig. 13 is characteristic of aggressive competition from the LTE side, thus resulting in the channel capture effects.

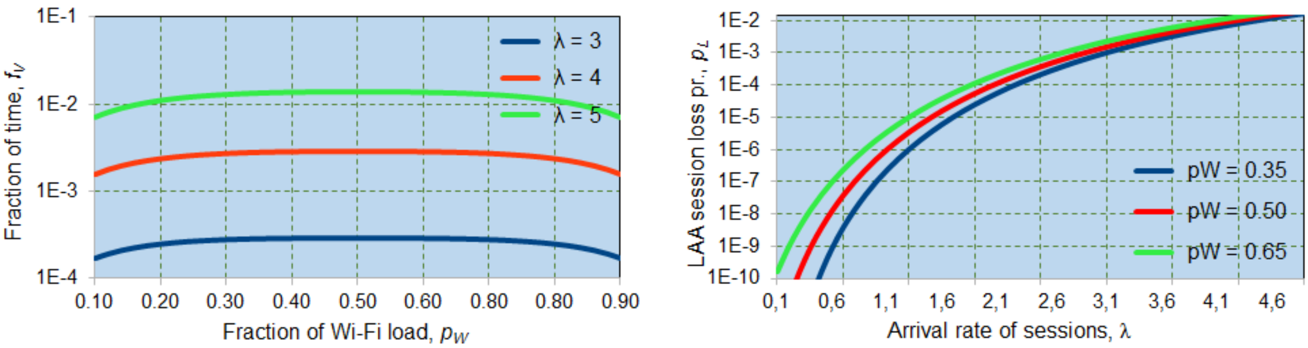
D. IMPERFECTION ANALYSIS

As discussed previously, the proposed channel sharing mechanism by design does not have any means to control the process of session acceptance at Wi-Fi APs. Hence, there may be situations when the performance guarantees of LTE sessions cannot be met perfectly. This, for example, occurs when the system operates at its maximum loading and there are further arrivals of Wi-Fi sessions, see Section IV. These sessions are then accepted by the system, thus potentially violating the fairness and QoS criteria. In this subsection,



(a) (b)

FIGURE 13. Throughput and Jain's fairness index for the LBT-based LAA implementation. (a) Throughput. (b) Jain's fairness index.



(a) (b)

FIGURE 14. Analytical measure of system performance: fraction of time when QoS is violated and session loss probability for LTE. (a) Fraction of time when QoS is violated. (b) Session loss probability for LTE.

by utilizing our analytical model developed in Section IV, we quantify the fraction of time spent in the situation when the QoS guarantees might be violated.

Accordingly, Fig. 14(a) demonstrates the fraction of time when the QoS is violated, f_V, as a function of the fraction of Wi-Fi sessions, p_W, for different values of the session arrival rate, as computed with (15). As one may observe, the parameter of interest first grows up to $p_W = 0.5$ and then decreases as p_W increases further. This particular behavior may be explained by the nature of the set of states, where QoS is violated. Recalling Fig. 8, we see that the fraction of time, f_V, depends on the probability of entering the QoS violation set as well as on the time spent in that set. The former is mainly dictated by the fraction of LTE sessions, p_L, while the latter is determined by p_W. Therefore, by increasing p_W the time spent in the QoS violation states grows, but the probability of entering this set is becoming smaller as p_L decreases. Analyzing the absolute numbers, we learn that even for rather high arrival rates, e.g., $\lambda = 5$, the relative time spent in the QoS violation states is slightly over 1%. This explains the results observed in Fig. 9 and Fig. 10.

Satisfactory performance of the proposed channel sharing mechanism comes at the expense of LTE session service. We specifically note that this is a mandatory move to ensure fairness of Wi-Fi sessions mindful of the QoS guarantees for the *accepted* LTE sessions. Here, Fig. 10 demonstrates the LTE session loss probability as a function of the arrival rate into the system for different values of the fraction of Wi-Fi sessions, p_W, as estimated with (10). As expected, one may observe exponential behavior of p_L when the arrival rate of sessions to the system increases for all the considered values of p_W. Then, the only way to improve the LTE session loss probability while still satisfying the fairness and QoS constraints, is to increase the number of LAA BSs deployed within the area of interest.

VI. CONCLUSIONS

In this paper, we proposed a channel sharing mechanism for LTE/Wi-Fi coexistence in the LAA system. Our contributed scheme is based on two core algorithms: the adaptive duty cycle and the LAA CAC. By relying on a mixture of simulation- and analysis-based methods, we demonstrated that a joint implementation of these two algorithms not only ensures fair allocation of radio resources between Wi-Fi and LTE sessions that share the common channel as required by 3GPP [9], [11], but also provides QoS guarantees in terms of both throughput and delay to the LTE sessions. The only external information required on the Wi-Fi APs that share the common channel is the number of currently active sessions, which can be estimated dynamically at the LAA BS by continuously monitoring this shared channel. As a result, the proposed channel sharing mechanism does not require co-located LTE/Wi-Fi deployments.

Utilizing adaptive duty cycle with CAC instead of LBT-based access reduces the amount of signaling on the shared channel. Selective time-slot management does not require the use of dedicated algorithms that check whether the channel is free before transmission, thus offering more transmission opportunities for both LTE and Wi-Fi. The default rounding operation when allocating the time slots to each user has the added benefit of providing a guard interval at the edges between on and off periods of a duty cycle. This further reduces interference due to transmission delays. Adaptive channel management requires quick and efficient adjustment of parameters, thus somewhat increasing the workload at the LAA BSs. Despite this overhead, the proposed algorithm balances the loading on the LAA BSs in the scenarios where unlicensed bands are already highly congested.

The co-located use of Wi-Fi and LTE in the proposed scheme could lead to a number of issues at the side of Wi-Fi UE. Particularly, there should be a way for Wi-Fi UEs to understand that the medium is currently busy. For seamless implementation, this needs to be done without modifying the operation of the Wi-Fi MAC layer. We foresee a range of engineering solutions to address this problem. For example, one could modify the Wi-Fi driver such that it no longer returns ''network unavailable'' when the medium busy time (captured with the physical busy channel assessment function) exceeds a certain vendor-dependent threshold. Alternatively, an LAA-compatible LTE BS may generate 'fake' RTS-CTS handshakes during its channel allocation to update the network allocation vector (NAV) values at Wi-Fi UEs.

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