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Performance Assessment of QoS-Aware LTE Sessions Offloading Onto LAA/WiFi Systems

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ABSTRACT Fifth-generation (5G) cellular systems are expected to orchestrate a variety of air interfaces. In this heterogeneous setting 4G, LTE systems will remain of special importance providing service over a relatively large area not covered with the 3GPP new radio technology. However, the scarcity of radio resources below 6 GHz as well as constantly increasing user traffic demands call for efficient offloading strategy from the LTE network. In this paper, we consider and compare two LTE session offloading strategies, including LAA and WiFi offloading. Although by design, the LAA system supports quality-of-service (QoS) guarantees in terms of minimum throughput, the assured performance might still be violated by resource reallocations when satisfying the compulsory fairness criteria. To assess and compare the performance of these schemes, we develop an analytical framework that takes into account specifics of duty-cycle schedule-based Licensed Assisted LTE Access (LAA) system with connection admission control (CAC), resource reallocation mechanism, and realistic elastic traffic nature. As a special case of the developed framework, we also address the offloading of QoS-aware LTE sessions into conventional WiFi. Our numerical results indicate that WiFi offloading is characterized by a significantly greater number of offloaded sessions. However, this advantage comes at the expense of severe performance degradation in terms of minimum throughput guarantees. Implementing CAC procedures, LAA efficiently addresses this problem. We conclude that WiFi offloading of QoS-aware LTE sessions can be used in light traffic conditions only. On the other hand, offloading to the schedule-based LAA system allows preserving QoS over a wide range of arrival traffic statistics.

INDEX TERMS LTE, Licensed Assisted Access, LAA, QoS, WiFi, elastic traffic, session interruption probability, drop probability, mean bit rate.

I. INTRODUCTION

Along with the drastically increasing rates at the air interface, the recent strong push from 3GPP towards standardization of fifth generation (5G) wireless systems promises to bring an unprecedented flexibility for network operators. In addition to New Radio (NR, [1]) technology operating in millimeter wave (mmWave) frequency band dramatically improving the rates at the access interface, 5G is expected to bring new system, service delivery mechanisms and network architecture that would potentially allow for efficient orchestration of future heterogeneous wireless systems [2], [3].

In contrast to previous generation of cellular systems, 5G is not expected to completely abandon or replace the existing radio technologies with the NR air interface. As a result of limited coverage at mmWave frequencies [4], NR is assumed to provide isolated high capacity islands in high demand traffic areas such as squares, shopping malls, airports, etc. The LTE is expected to still play a crucial role in service provisioning in 5G systems enabling not only signaling support for the LTE-anchored NR deployments but serving as a bearer for areas where no NR connectivity is available.

The scarcity of bandwidth available below 6GHz force network operators and standardization bodies to seek for cost efficient solution to expand the spectrum available for

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LTE systems. Over the last several years, two technologies have been proposed, namely Licensed Assisted LTE Access (LAA, [5]) and Licensed Shared LTE Access (LSA, [6]–[8]). The latter specifies temporal spectrum leasing techniques for network operators while the former assumes simultaneous use of LTE and IEEE 802.11 wireless local area networks (WLAN) in unlicensed industrial, scientific and medical bands, 2.4GHz and 5.1GHz.

LAA is introduced in 3GPP Release 13 as part of LTE-Advanced [9]. It uses carrier aggregation to combine LTE in the licensed and unlicensed bands. According to recent performance evaluation studies, LAA promises faster data rates and more responsive user experience [10], [11]. A mobile operator using LAA can support Gigabit Class LTE with as little as 20 MHz of licensed spectrum. By maintaining a persistent anchor in the licensed spectrum carrying control and signaling information, the user experience is promised to be seamless and reliable [11]. LAA promises the fast time to the market and can be implemented as a part of LTE offering an appealing option for network operators [12].

A. RELATED WORK

Quoting 3GPP TR.36.889 [11], the major requirement for LAA implementation is ''*LAA network should not affect existing WiFi neighbors any more than another WiFi network operating at the same channel*''. However, 3GPP does not explicitly standardize the channel access procedure leaving this question for vendors' implementation. In response to the call for proposals two major designs have been suggested. According to the first approach, a shim layer responsible for listen-before-talk functionality (LBT) is introduced to the LTE protocol stack making LTE complaint with the distributed random channel access of IEEE 802.11 WiFi technologies. Particular solutions vary from simple ALOHA approach to very complex CSMA/CA-like access with multiple back-off stages [13], [14]. Operating in this mode LAA systems may satisfy the 3GPP interference requirement but at the same time completely neglect the critical feature of LTE systems – strict quality of service (QoS) guarantees at the air interface.

According to the second conceptual approach to LAA design, LAA-compatible LTE base station (BS) is provided the full control over the shared medium [15]. Operating in this mode LAA BS is responsible for fair division of the channel, scheduling of resources and should also implement connection admission control (CAC) policy for its own connections such that both targets are achieved: (i) fair division of resources and (ii) QoS maintenance for LAA connections. Several studies addressed various aspects of such systems [16]–[19].

In spite of significant efforts devoted to development of 3GPP-compliant LAA system the performance assessment framework has been proposed in [20] only. The authors have proposed schedule-based design of the LAA MAC layer with CAC mechanism and dynamic duty cycle adaptation to provide both throughput and delay requirements to LAA sessions. However, the developed model assumes that the LAA sessions durations are such that the probability of WiFi session arrival time during the service time of LAA session is negligible. As a result, in spite of the system being vulnerable to QoS degradation of ongoing LAA sessions, this behavior is not captured in the proposed model.

B. OUR CONTRIBUTIONS

In this study, we consider and compare performance of offloading schemes from LTE onto schedule-based LAA system and conventional WiFi technology. Schedule-based LAA system implements CAC and constant duty cycle functionalities providing both throughput guarantees to LAA sessions and ensuring fairness of resource allocation between WiFi and LAA connections. Assuming elastic traffic sessions, we use the tools of queuing theory to develop performance evaluation framework that explicitly takes into account QoS degradation of LAA sessions caused by WiFi sessions arrivals. As a special case of the framework, we also characterize WiFi offloading mechanism. We then proceed comparing LAA system against the WiFi offloading technique.

The main contributions of our study are:

- performance evaluation framework capturing user- and system-centric metrics of QoS-aware schedule-based LAA system design with CAC mechanism, constant duty cycle and realistic elastic traffic arrivals flows;
- performance comparison of traffic offloading strategies from LTE onto QoS-aware LAA and conventional WiFi systems characterizing performance degradation experienced by QoS-aware sessions;
- our numerical results show that the use of LAA not only improves the overall offloading performance due to better use of radio resources, but provides performance guarantees in terms of minimum throughput and bounded delay.

The rest of the paper is organized as follows. In Section II we briefly outline 3GPP LAA architecture and introduce the considered schedule-based QoS-aware LAA system. The system model is introduced in Section III. The performance modeling framework is developed in Section IV. Numerical results and comparison of offloading strategies are presented in Section V. Conclusions are drawn in the last section.

II. LAA SYSTEM ARCHITECTURE

In this section we first briefly introduce 3GPP LAA service architecture and then proceed specifying the details of the considered LAA implementation.

A. 3GPP LAA ARCHITECTURE

Opportunistic use of unlicensed spectrum is becoming an important complement for operators to meet the growing traffic demands. 3GPP along with IEEE, WiFi Alliance, WiFi manufacturers, and stakeholders have contributed significantly to analyze new coexistence techniques starting from Rel-12. The successes of the first tests on interworking between LTE and WiFi prompted 3GPP to deepen coexis-

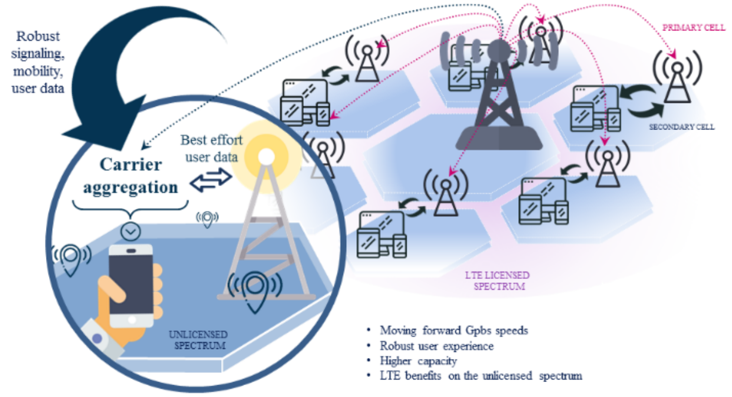

FIGURE 1. The generic 3GPP LAA service principles.

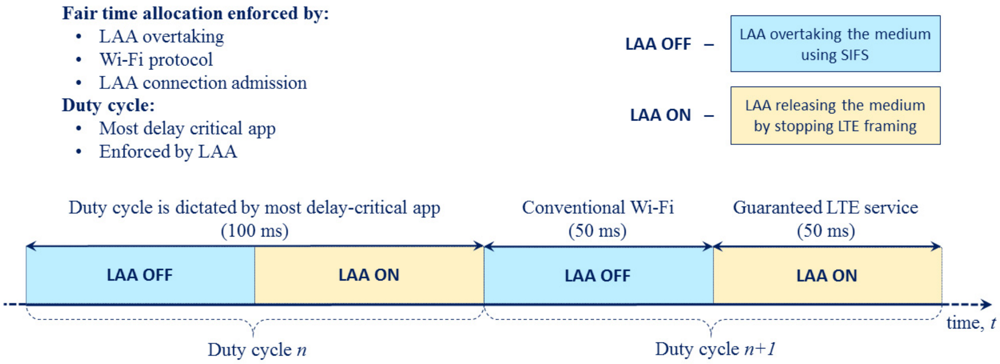

FIGURE 2. The considered duty-cycle based LAA architecture.

tence studies. New architectures, interfaces, and protocols have been designed, leading to an increase of over 70% of the throughput over the use of WiFi alone. Despite all the benefits, this is not enough; improvement for WiFi under mobile or roaming scenarios are required, and companies see benefits for operators to use unlicensed spectrum mainly with a unified network, in order to offer operational cost savings, improved spectral efficiency and better user experience.

Starting with Rel-13, 3GPP decided to undertake the study of Licensed-Assisted Access (LAA), to provide consumers and operators with new technique for improve user experience on the unlicensed spectrum, while coexisting at the same time with all other technologies in the 5 GHz unlicensed band, see Fig. 1. According to 3GPP [11] LAA implementation requires the joint implementation of the following three mechanisms: (i) carrier selection, (ii) carrier aggregation, and (iii) LBT mechanism. The use of LAA is to maintain high performance through LTE on the licensed spectrum and use a secondary carrier based on LTE on the unlicensed spectrum for data rate boost. The central focus of the studies was fair sharing and coexistence with WiFi where the criterion used to ensure coexistence was that a LAA network does not affect existing WiFi neighbors no more than another WiFi network. As a secondary objective, LAA's design required the creation of a single global solution that would allow compliance with any regional regulatory requirements and maintain an effective and fair coexistence among LAA networks deployed by different operators. To be friendly and fair, the best coexistence mechanism has been evaluated in RAN1 and specified in TR 36.889. Listen before Talk (LBT) is selected as a channel access scheme for LAA system. This method first senses the medium and then transmits if the channel is idle.

Following [11] there are two types of foreseen LAA implementations: co-located and stand alone. The first type is when LTE is implemented in a single module with WiFi. In this case, a co-located LTE/WiFi BS possess all the information about the shared environment and have much more options for enabling fairness and QoS guarantees. However, recall that LAA-enabled BSs are expected to operate in uncontrolled environment, where there might be non-LAA complaint equipment. Thus, we consider standalone case, where no additional information except for the one gathered from the shared environment are available.

B. THE SCHEDULE-BASED LAA ARCHITECTURE

In this paper, we consider duty-cycle based LAA architecture initially proposed in [19] and [20]. The proposed channel access procedure is illustrated in Fig. 2. According to it, LAA is in full control of the channel access and uses short interframe spacing (SIFS) of 802.11 WiFi to enforce the resource allocation over the medium by overtaking and releasing the channel. The duration of the duty cycle is dictated by the LTE session having the strictest latency requirements and is assumed to be set constant. When LAA occupies the medium, the standard LTE OFDMA-based framing is enforced. Once the medium is released, WiFi stations perform competition for the shared resource following IEEE 802.11 CSMA/CA mechanisms with binary exponential back-off (BEB).

To ensure fairness of resources allocation LAA BS monitors traffic flow during WiFi time allocation of the duty-cycle and keeps track of the number of WiFi sessions competing for resources. As LAA should have no control over acceptance of WiFi sessions, upon arrival of new WiFi session the time share of the duty cycle allocated to WiFi and LAA is recomputed. The resource allocation during the LAA share of the duty-cycle is updated accordingly. Resources among WiFi stations are divided according to CSMA/CA MAC algorithm during the WiFi part of the duty-cycle. Time allocations are recomputed when WiFi session leaves the system as well.

To provision QoS guarantees to LAA sessions in terms of per-session throughput, LAA BS implements the CAC mechanism. According to it, once LAA session arrives, CAC recomputes the share of duty-cycle and enforces the allocation if and only of the new session does not violate fairness of resource allocation between WiFi and LAA. Otherwise, the session is rejected. More details on handling of session arrival and departure events are provided in [20].

Note that although the described system attempts all the efforts to ensure QoS guarantees to ongoing LAA sessions, the throughput guarantees might still be violated. This particularly may happen when a WiFi session arrives to the system and the resulting time allocations to ongoing LAA session do not allow to meet the throughput guarantees. The system may thus be configured to drop one or more LTE sessions such that the rest of sessions do not experience performance degradation.

III. SYSTEM MODEL

In this section, we formulate the system model of the LAA and WiFi traffic offloading strategies allowing to reduce the load imposed on LTE macro BS. We assume that the offloading process from LTE BS is characterized by a certain intensity of sessions, see Fig. 3. Each session is characterized by a certain minimum throughput that has to be maintained during the whole duration of the session. In case of LAA offloading, LAA BS is assumed to implement CAC algorithm and duty-cycle procedure as described in Section II.B. In addition to LAA BS, the same channel is simultaneously used by WiFi access point (AP) to serve its sessions arriving at rate λ_W. LAA BS is assumed to compete for resources with WiFi AP satisfying 3GPP fairness requirements and at the same time providing QoS guarantees to LAA arrivals. If upon arrival of

LAA BS session, the overall number of sessions in the system is such that fairness or QoS guarantees of ongoing sessions will be violated, an arriving session is dropped. Furthermore, if upon arrival of a new WiFi session, the overall number of sessions in the system is such that QoS guarantees of one or more sessions are going to be violated, the service process of one of the LAA sessions will be interrupted. As an alternative approach we consider offloading of LTE QoS-aware sessions to WiFi AP.

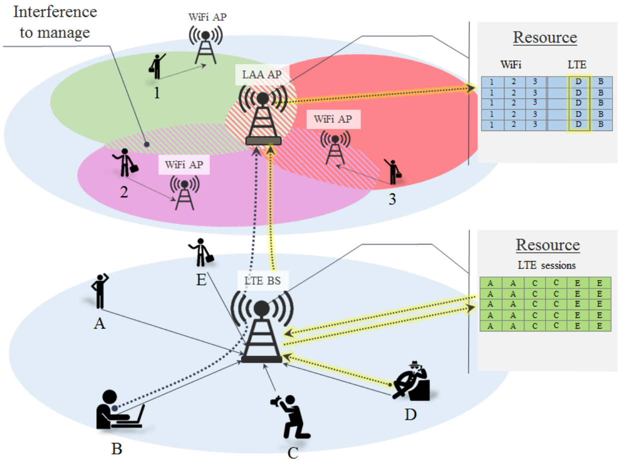

FIGURE 3. Traffic offloading onto LAA from macro LTE BS.

Let us introduce the notation, which we will use further to analyze the operation of offloading strategies. We consider two systems, each operating using a channel with the raw rate of C bandwidth units (b.u.) and serving two classes of elastic flows. The first class corresponds to the sessions served by WiFi AP. The second class is associated with the offloaded sessions that are served using either LAA BS or WiFi AP depending on the considered offloading strategy. Sessions of both classes arrive according to Poisson processes with intensities λ_W and λ_L, respectively. The rates of elastic flows are assumed to be exponentially distributed with means λ_W and λ_L for WiFi and offloaded classes. Resource requirements of Wi-Fi and LAA sessions are characterized by constant demand sizes, θ_W and θ_L. We denote the corresponding offered loads as $\rho_W = \lambda_W \theta_W$ and $\rho_L = \lambda_L \theta_L$.

IV. PERFORMANCE EVALUATION FRAMEWORK

In this section, we formulate our performance evaluation framework. First, we formalize and solve the model of traffic offloading onto LAA system introduced in Section II. Then, we address WiFi offloading strategy by replacing LAA system with 802.11 WiFi technology.

A. OFFLOADING ONTO LAA BS

To describe the process of servicing sessions in the LAA system we use a two-dimensional continuous-time Markov chain (CTMC) formulated as follows. Consider CTMC $\mathbf{X}(t) = \{N_W(t), N_L(t), t > 0\}$, where $N_W(t)$ is the number of WiFi sessions, $N_L(t)$ is the number of offloaded LTE sessions in the system at the moment t. Due to the elastic nature of sessions, characterized by uniform distribution of channel rate C between all the simultaneously served elastic flows, and taking into account that the arrival process is Poisson in nature while service times are exponentially distributed, the behavior of the system could be described by the Markov chain $\mathbf{X}(t)$ on the state space

$$\mathbf{X} = \{(n_W, n_L) : n_W \geq 0, n_L \geq 0, \cdot n_L \geq 0, L \cdot I(n_L > 0) \cdot \\ \cdot (n_W + n_L) \leq C\} \quad (1)$$

where n_W is the current number of elastic flows generated by WiFi sessions, n_L is the current number of elastic flows generated by LTE sessions.

Note that elastic flow bitrate of the WiFi or LTE classes is $C/(n_W + n_L)$, provided that the total number of transferred flows is less or equal to $\lfloor C/L \rfloor$, otherwise the bitrate is equal to C/n_W. We denote by $N_L = \lfloor C/L \rfloor$ the maximum number of elastic flows generated by LTE sessions.

The ergodic bitrates of WiFi and LAA sessions, d_W or d_L, depend on the state $(n_W, n_L) \in \mathbf{X}$ of the system. To determine them we need to consider LAA CAC mechanisms scheme, first, from the standpoint of the WiFi sessions, and, second, from the standpoint of the LTE sessions. When the WiFi elastic flow arrives, three cases are possible:

- if the first-class flow finds the LAA system servicing less than N_L elastic flows, then the flow will be accepted on bitrate $d_W = C/(n_W + n_L)$ b.u.;
- if the first-class flow finds the LAA system servicing N_L elastic flows, and the number of second-class elastic flows is greater than 0, i.e. $n_L > 0$, then the flow will be accepted on bitrate $d_W = C/(n_W + n_L)$ b.u. by interrupt one second-class flow;
- if the first-class flow finds the LAA system servicing N_L or greater elastic flows, and the number of second-class elastic flows equal to 0, i.e. $n_L = 0$, then the flow will be accepted on bitrate $d_W = C/n_W$ b.u.

When LAA session arrives two cases are possible:

- if the flow finds the LAA system servicing less than N_L elastic flows, then the flow will be accepted on bitrate $d_L = C/(n_W + n_L)$ b.u.;
- otherwise the flow will be blocked without any after-effect on the corresponding Poisson process arrival rate.

In view of these rules, the service rates of incoming WiFi or LTE sessions are defined as $C/((n_W + n_L)\theta_W)$ and $C/((n_W + n_L)\theta_L)$, respectively. Then, the data rates of the model $a\left((n_W, n_L)\left(n'_W, n'_L\right)\right)$, needed to form the infinitesimal generator $\mathbf{A}$ of CTMC $\mathbf{X}(t)$ for an arbitrarily chosen state $(n_W, n_L) \in \mathbf{X}$, have the following form

$$\begin{cases} a(n_W, n_L)(n_W + 1, n_L) = \lambda_W, \\ a(n_W, n_L)(n_W - 1, n_L) = \dfrac{C}{(n_W + n_L)\theta_W} n_W, \\ a(n_W, n_L)(n_W, n_L + 1) = \lambda_L, \\ a(n_W, n_L)(n_W, n_L - 1) = \dfrac{C}{(n_W + n_L)\theta_L} n_L, \\ a(n_W, n_L)(n_W + 1, n_L - 1) = \lambda_W. \end{cases} \quad (2)$$

The overall structure of the state transition diagram of the defined CTMC model is shown in Figure 5, while the detailed transition rates for two boundary and one inner states are illustrated in Figure 4.

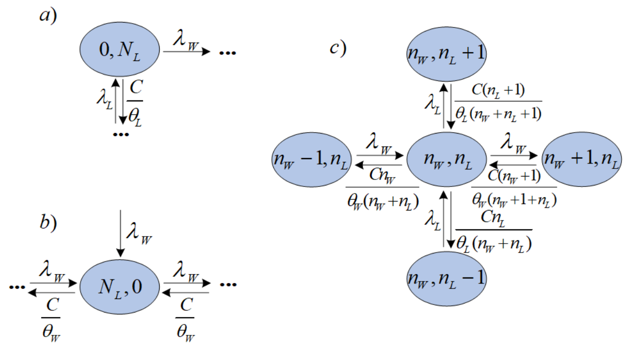

FIGURE 4. The state transition diagram for individual states of the LAA system: (a) data rates for boundary state $(0, N_L)$; (b) data rates for boundary state $(N_L, 0)$; (c) data rates for central state (n_W, n_L).

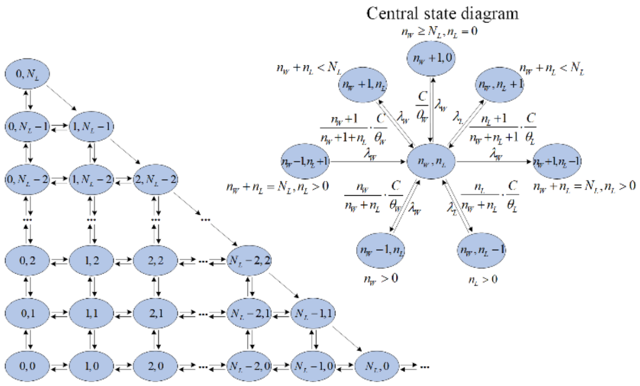

FIGURE 5. The general view of the state transition diagram for the LAA system with WiFi and LTE sessions.

Now, CTMC $\mathbf{X}(t)$ representing the system's states could be described by the following system of equilibrium equations

$$\begin{aligned} &p(n_W, n_L)\left[\lambda_W \cdot (I(n_W \geq N_L, n_L = 0)\right. \\ &\quad + I(n_W + n_L < N_L) + I(n_W + n_L = N_L, n_L > 0)) \\ &\quad + \lambda_L \cdot I(n_W + n_L < N_L) + \frac{Cn_L}{(n_W + n_L)\theta_L} \cdot I(n_L > 0) \\ &\quad \left. + \frac{Cn_W}{(n_W + n_L)\theta_W} \cdot I(n_W > 0)\right] = p(n_W + 1, 0)\frac{C}{\theta_W} \\ &\quad \cdot I(n_W \geq N_L, n_L = 0) + p(n_W - 1, n_L)\lambda_W \\ &\quad \cdot I(n_W > 0) + p(n_W, n_L - 1)\lambda_L \\ &\quad \cdot I(n_L > 0) + p(n_W - 1, n_L + 1)\lambda_W \\ &\quad \cdot I(n_W + n_L = N_L, n_L > 0) + p(n_W, n_L + 1) \\ &\quad \cdot \frac{C(n_L + 1)}{(n_W + n_L + 1)\theta_L} \cdot I(n_W + n_L < N_L) \\ &\quad + p(n_W + 1, n_L)\frac{C(n_W + 1)}{(n_W + n_L + 1)\theta_W} \cdot I(n_W + n_L < N_L), \end{aligned} \quad (3)$$

where $(p(n_W, n_L))_{(n_W, n_L) \in \mathbf{X}} = \mathbf{p}$ is the stationary state probability distribution.

As a result of session interruption mechanism, the CTMC $\mathbf{X}(t)$ is not a reversible Markov chain. Nevetheless, the system stationary state probability distribution $p(n_W, n_L)$, $(n_W, n_L) \in \mathbf{X}$ could be numerically computed as the solution of the system of equilibrium equations (3), written in the following form $\mathbf{p} \cdot \mathbf{A} = \mathbf{0}$, $\mathbf{p} \cdot \mathbf{1}^{\mathbf{T}} = \mathbf{1}$, where the elements $a\left((n_W, n_L)\left(n_W^{'}, n_L^{'}\right)\right)$ of the transposed infinitesimal generator, $\mathbf{A}$, are defined as

$$a\left((n_W, n_L)\left(n_W^{'}, n_L^{'}\right)\right) = \begin{cases} \lambda_W, & n_W^{'} = n_W + 1, n_L^{'} = n_L - 1, \\ & n_L > 0, \quad n_W + n_L = N_L \\ & \text{or } n_W^{'} = n_W + 1, n_L^{'} = n_L, n_W + n_L < N_L \\ & \text{or} n_W^{'} = n_W + 1, n_L^{'} = n_L = 0, n_W \geq N_L, \\ \lambda_L, & n_W^{'} = n_W, n_L^{'} = n_L + 1, n_W + n_L < N_L, \\ & \dfrac{n_W}{n_W + n_L} \cdot \frac{C}{\theta_W}, n_W^{'} = n_W - 1, n_L^{'} = n_L, n_W > 0, \\ & \dfrac{n_L}{n_W + n_L} \cdot \dfrac{C}{\theta_L}, n_W^{'} = n_W, n_L^{'} = n_L - 1, n_L > 0, \\ *, & n_W^{'} = n_W, n_L^{'} = n_L, \\ 0, & \text{otherwise}, \end{cases} \tag{4}$$

where $* = -(\lambda_W + \lambda_L \cdot I\{n_W + n_L < N_L\} + \frac{Cn_W}{(n_W + n_L)\theta_W} \cdot$ $\cdot I\{n_W > 0\} + \frac{Cn_L}{(n_W + n_L)\theta_L} \cdot I\{n_L > 0\})$.

Having found the stationary state probability distribution $p(n_W, n_L)$, $(n_W, n_L) \in \mathbf{X}$, one can compute the performance measures of the considered LAA system as follows.

- LTE session drop probability, B, i.e., the probability that arriving LTE session is dropped is given by

$$B = \sum_{n_W=0}^{N_L-1} p(n_W, N_L - n_W) + \sum_{n_W=N_L}^{\infty} p(n_W, 0); \tag{5}$$

- LTE session interruption probability, I_1, that is, the probability that an arbitrary LTE session accepted to the system is dropped during the service is

$$I_1 = \sum_{n_W=0}^{N_L-1} \frac{\lambda_W}{\lambda_W + \lambda_L + \frac{Cn_W}{N_L\theta_W} \cdot I(n_W > 0) + \frac{C(N_L - n_W)}{N_L\theta_L}} \cdot p(n_W, N_L - n_W); \tag{6}$$

- LTE session interruption probability, I_2, that is, the probability, that the specific LTE session accepted to the system is lost during the service is

$$I_2 = \sum_{n_W=0}^{N_L-1} \frac{1}{N_L - n_W} \cdot \frac{\lambda_W}{\lambda_W + \lambda_L + \frac{C(N_L - n_W)}{N_L\theta_L} + \frac{Cn_W}{N_L\theta_W} \cdot I(n_W > 0)} \cdot p(n_W, N_L - n_W); \tag{7}$$

- Share of elastic flows γ generated by LTE sessions that successfully complete their service in the LAA system, i.e. the share of elastic flows that will not be blocked and the service of which will not be interrupted

$$\gamma = (1 - B)(1 - I_2)\lambda_L; \tag{8}$$

- Mean bitrate $\bar{d}_W$ for elastic flows generated by WiFi sessions (9), as shown at the bottom of this page.
- Mean bitrate $\bar{d}_L$ for elastic flows generated by LTE sessions

$$\bar{d}_L = \frac{\sum_{n_L=1}^{N_L} \sum_{n_W=0}^{N_L-n_L} \frac{C}{n_W + n_L} p(n_W, n_L)}{\sum_{n_L=1}^{N_L} \sum_{n_W=0}^{N_L-n_L} p(n_W, n_L)}; \tag{10}$$

- Mean number $\bar{N}_W$ of elastic flows generated by WiFi sessions in the system

$$\bar{N}_W = \sum_{n_W=1}^{N_L-1} n_W \sum_{n_L=0}^{N_L-n_W} p(n_W, n_L) + \sum_{n_W=N_L}^{\infty} n_W p(n_W, 0); \tag{11}$$

- Mean number $\bar{N}_L$ of elastic flows generated by LTE sessions in the system

$$\bar{N}_L = \sum_{n_L=1}^{N_L} n_L \sum_{n_W=0}^{N_L-n_L} p(n_W, n_L); \tag{12}$$

- Part of the total data rate c_1 allocated for transmission of elastic flows generated by WiFi sessions

$$c_1 = \sum_{n_W=1}^{N_L-1} \sum_{n_L=0}^{N_L-n_W} \frac{n_W}{n_W + n_L} p(n_W, n_L) + \sum_{n_W=N_L}^{\infty} p(n_W, 0); \tag{13}$$

- Part of the total data rate c_2 allocated for transmission of elastic flows generated by LTE sessions

$$c_2 = \sum_{n_L=1}^{N_L} \sum_{n_W=0}^{N_L-n_L} \frac{n_L}{n_W + n_L} p(n_W, n_L); \tag{14}$$

- Jain's fairness index J allowing to assess the fairness of resource division between the elastic flows generated by

$$\bar{d}_W = \frac{\sum_{n_W=1}^{N_L-1} \sum_{n_L=0}^{N_L-n_W} \frac{C}{n_W + n_L} p(n_W, n_L) + \sum_{n_W=N_L}^{\infty} \frac{C}{n_W} p(n_W, 0)}{\sum_{n_W=1}^{N_L-1} \sum_{n_L=0}^{N_L-n_W} p(n_W, n_L) + \sum_{n_W=N_L}^{\infty} p(n_W, 0)}; \tag{9}$$

WiFi and LTE sessions

$$J = \sum\nolimits_{(n_W,n_L)\in\mathbf{X}} J(n_W,n_L)p(n_W,n_L), \tag{15}$$

where $J\left(n_W,n_L\right) = \left(\sum_{i=1}^{n_W+n_L} \frac{C}{(n_W+n_L)}\right)^2 \cdot \frac{1}{(n_W+n_L)\sum_{i=1}^{n_W+n_L}\frac{C^2}{(n_W+n_L)^2}} = 1.$

Note that the values of the Jain's fairness index vary from 0 to 1. The higher the value of the index is, the better the fairness of the resource allocation across sessions becomes.

B. OFFLOADING ONTO WiFi AP

In contrast to the LAA system analyzed above, when the regular QoS-aware LTE session is offloaded to WiFi AP, the QoS requirements may not be met. The reason is that in the considered WiFi offloading model bitrates of elastic flows generated by LTE sessions do not have the threshold minimum value and may freely change depending on the availability of system resources, i.e., $d_W \geq 0$ and $d_L \geq 0$.

Similar to the LAA offloading strategy we consider the two-dimensional CTMC $\mathbf{Y}(t) = \{N_W(t), N_L(t), t > 0\}$, where $N_W(t)$ is the number of WiFi sessions, $N_L(t)$ is the number of offloaded LTE sessions in the system at the moment t. However, in contrast to the previous case the current number n_L of elastic flows generated by LTE sessions is unlimited, i.e. n_L could be greater than N_L. Then the behavior of the system could be described by the Markov chain on the state space:

$$\mathbf{Y} = (n_W,n_L) : n_W \geq 0, n_L \geq 0. \tag{16}$$

Due to the lack of any QoS support in WiFi, all the sessions are always accepted to the system. Since we consider the elastic sessions, bitrates d_W and d_L are equal to each other, depend on the state $(n_W,n_L) \in \mathbf{Y}$ of the system and defined by $C\big/(n_W+n_L)$. The service time of incoming WiFi and LTE session is $(n_W+n_L)\,\theta_W\big/C$ and $(n_W+n_L)\,\theta_L\big/C$ respectively. This implies that the data rates of the model forming the infinitesimal generator $\mathbf{B}$ of Markov chain $\mathbf{Y}(t)$ do not include an element $b(n_W,n_L)(n_W+1,n_L-1)$. For an arbitrarily chosen state $(n_W,n_L) \in \mathbf{Y}$ the rates are

$$\begin{cases} b(n_W,n_L)(n_W+1,n_L) = \lambda_W, \\ b(n_W,n_L)(n_W-1,n_L) = \dfrac{C}{(n_W+n_L)\,\theta_W} n_W, \\ b(n_W,n_L)(n_W,n_L+1) = \lambda_L, \\ b(n_W,n_L)(n_W,n_L-1) = \dfrac{C}{(n_W+n_L)\,\theta_L} n_L. \end{cases} \tag{17}$$

The state transition diagram is shown in Figure 6.

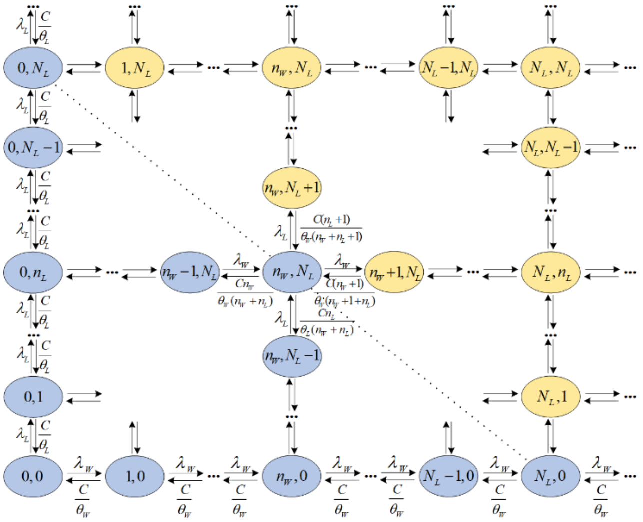

FIGURE 6. The general view of the state transition diagram for the WiFi system with WiFi and LTE sessions.

CTMC $\mathbf{Y}(t)$ representing the evolution of the system states is described by the following system of equilibrium equations

$$\begin{aligned} p(n_W,n_L)&\left(\lambda_W + \lambda_L + \frac{Cn_W}{(n_W+n_L)\,\theta_W}\cdot I(n_W>0)\right.\\ &\left.+\frac{Cn_L}{(n_W+n_L)\,\theta_L}\cdot I(n_L>0)\right) = p(n_W-1,n_L)\,\lambda_W \\ &\cdot I(n_W>0) + p(n_W,n_L-1)\,\lambda_L \cdot I(n_L>0) \\ &+p(n_W+1,n_L)\,\frac{C(n_W+1)}{(n_W+1+n_L)\,\theta_W} \\ &+p(n_W,n_L+1)\,\frac{C(n_L+1)}{(n_W+n_L+1)\,\theta_W}, \end{aligned} \tag{18}$$

where $(p(n_W,n_L))_{(n_W,n_L)\in\mathbf{Y}} = \mathbf{p}$ is the stationary state probability distribution.

In contrast to the CTMC $\mathbf{X}(t)$ describing the operation of the LAA system, the CTMC $\mathbf{Y}(t)$ is a reversible Markov chain (see Figure 6) and the stationary state probability distribution $p(n_W,n_L)$, $(n_W,n_L) \in \mathbf{Y}$ can found in the product form as the solution of the system of the local balance equations

$$\begin{cases} p(n_W,n_L)\,\dfrac{Cn_L}{\theta_L(n_W+n_L)} = \lambda_L p(n_W,n_L-1), \\ p(n_W,n_L)\,\dfrac{Cn_W}{\theta_W(n_W+n_L)} = \lambda_W p(n_W-1,n_L). \end{cases} \tag{19}$$

Solving the first equation of the system (19), we establish

$$\begin{aligned} &p(n_W,n_L) \\ &= p(n_W,n_L-1)\left(\frac{\lambda_L\theta_L}{C}\right)\cdot\frac{(n_W+n_L)}{n_L} \\ &= p(n_W,n_L-2)\left(\frac{\lambda_L\theta_L}{C}\right)^2\cdot\frac{(n_W+n_L)(n_W+n_L-1)}{n_L(n_L-1)} \\ &= \ldots = p(n_W,0)\left(\frac{\lambda_L\theta_L}{C}\right)^{n_L}\cdot\frac{(n_W+n_L)!}{n_W!}\cdot\frac{1}{n_L!} \\ &= \left(\frac{\rho_L}{C}\right)^{n_L}\cdot\frac{(n_W+n_L)!}{n_W!n_L!}. \end{aligned}$$

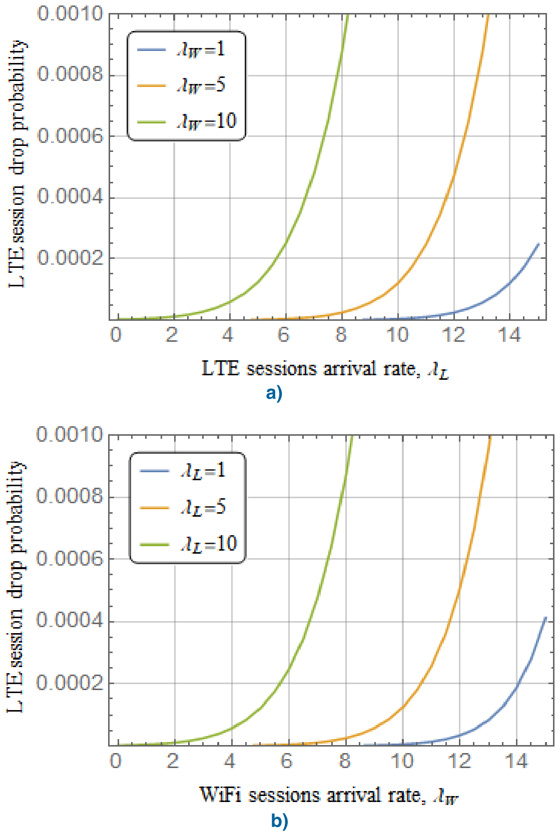

FIGURE 7. LTE session drop probability.

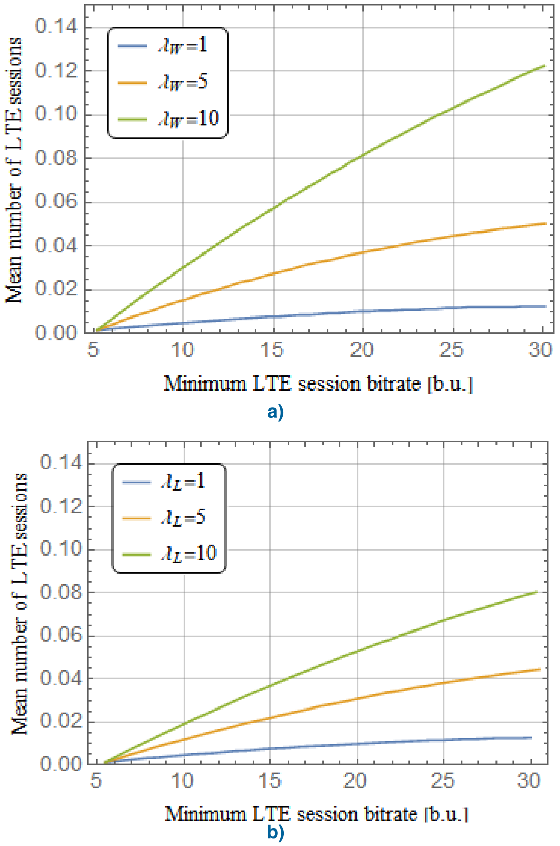

FIGURE 8. Mean number of LTE sessions in the system.

From the second equation of the system (19), we obtain

$$
\begin{aligned}
p\left(n_W, 0\right) &= p\left(n_W-1, 0\right)\left(\frac{\lambda_W \theta_W}{C}\right) \\
&= p\left(n_W-2, 0\right)\left(\frac{\lambda_W \theta_W}{C}\right)^2 = \ldots \\
&= p\left(0, 0\right)\left(\frac{\lambda_W \theta_W}{C}\right)^{n_W} = p\left(0, 0\right)\left(\frac{\rho_W}{C}\right)^{n_W}.
\end{aligned}
$$

To find $p\left(0, 0\right)$, we use the normalization condition,

$$
\begin{aligned}
&p\left(0, 0\right) \\
&= \left(\sum\nolimits_{(n_W, n_L) \in \mathbf{Y}} \left(\frac{\rho_W}{C}\right)^{n_W} \cdot \left(\frac{\rho_L}{C}\right)^{n_L} \cdot \frac{(n_W+n_L)!}{n_W! n_L!}\right)^{-1}.
\end{aligned} \tag{20}
$$

Taking into account (19) and (20), the stationary state probability distribution $p\left(n_W, n_L\right), \left(n_W, n_L\right) \in \mathbf{Y}$ of the WiFi system has the following product form

$$
\begin{aligned}
p\left(n_W, n_L\right) = &\left(\sum\nolimits_{(i,j) \in \mathbf{Y}} \left(\frac{\rho_W}{C}\right)^{i} \left(\frac{\rho_L}{C}\right)^{j} \frac{(i+j)!}{i! j!}\right)^{-1} \\
&\cdot \left(\frac{\rho_W}{C}\right)^{n_W} \left(\frac{\rho_L}{C}\right)^{n_L} \frac{(n_W+n_L)!}{n_W! n_L!}.
\end{aligned} \tag{21}
$$

Having obtained the stationary state probability distribution $p\left(n_W, n_L\right), \left(n_W, n_L\right) \in \mathbf{Y}$, we can calculate the performance characteristics of the WiFi offloading strategy as follows.

- Probability that the bitrate d_L of LTE sessions is less than L b.u. is given by

$$
P_L = 1 - \sum\nolimits_{n_W=0}^{N_L} \sum\nolimits_{n_L=0}^{N_L-n_w} p(n_W, n_L). \tag{22}
$$

- Mean number $\bar{N}_L$ of elastic flows generated by LTE sessions in the system

$$
\bar{N}_L = \sum\nolimits_{n_L=1}^{\infty} n_L \sum\nolimits_{n_W=0}^{\infty} p(n_W, n_L). \tag{23}
$$

V. NUMERICAL ANALYSIS OF OFFLOADING STRATEGIES

In this section we numerically characterize the considered traffic offloading strategies. We first address performance provided by LAA offloading strategy concentrating on the probability that the offloaded LTE session is not accepted to the system and the mean number of WiFi and LTE sessions in the system. Then, we describe performance of WiFi offloading mainly concentrating on probability that the throughput requirements for offloaded LTE session are not satisfied. Finally, we perform the direct comparison between the considered strategies addressing the degree of offloading using the overall number of connections as a metric of interest.

We consider the standard 20MHz wide channel. The average spectral efficiencies of WiFi and LTE are assumed to be 2bits/s/Hz and 3bits/s/Hz, respectively [21], [22]. We express

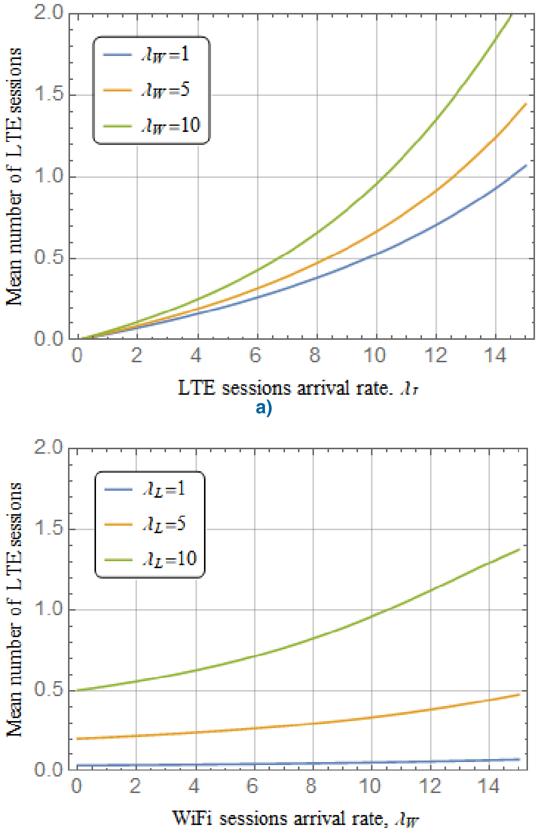

FIGURE 9. Mean number of LTE sessions in the system.

the minimum bitrate, L, required by LTE sessions in basic units (b.u.), where 1 b.u. equals to 0.1Mbps.

A. OFFLOADING ONTO LAA

We start characterizing performance of LAA offloading mechanism. To do that we consider the dependence of LTE session drop probability and mean number of active LTE sessions provided in Section IV on the arrival rate of elastic flows generated by WiFi and LTE sessions. The input parameters are summarized in Table 1.

TABLE 1. Input parameters for numerical analysis.

Parameter	Dynamic value		
	Scenario 1	Scenario 2	Scenario 3
WiFi sessions arrival rate, λ_W	1 – 15	15	15
LTE sessions arrival rate, λ_L	1,5,10	1 – 15	1,5,10
Minimum required bitrate, L	5 b.u.	5 b.u.	5 – 30 b.u.

Consider first the effect of WiFi and LTE session arrival rates on LTE session drop probability illustrated in Fig. 7. As one may observe, the response of the considered metric is qualitatively similar to both parameters. Indeed, the increase in both arrival rates brings more traffic to the system increasing the probability that the amount of available resources for arriving LTE session is insufficient.

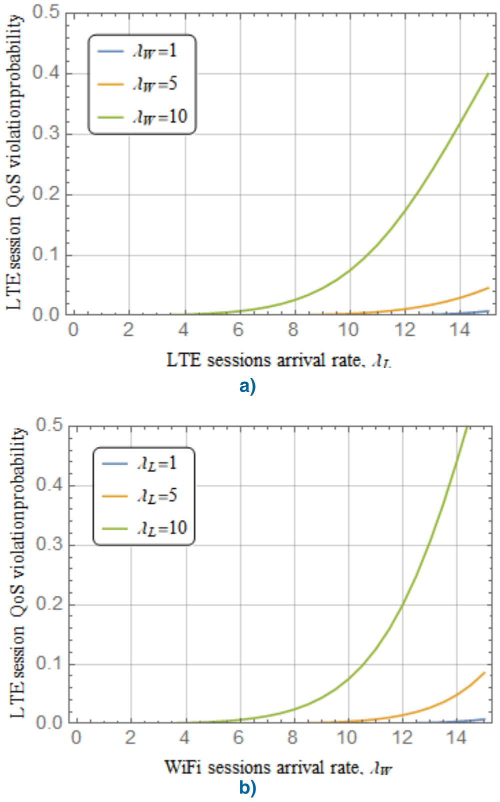

FIGURE 10. Probability that rate requirements are violated.

The distinguishing property of LAA system is ability to provide performance guarantees to LTE sessions. Fig. 8 illustrates the gain of offloading LTE sessions to LAA technology as a function of the minimum required LTE session bitrate, L, measured in b.u. for different LTE and WiFi session arrival rates. Analyzing the data, one may notice that for any values of LTE or WiFi session arrival rates the mean number of LTE sessions increases as the minimum LTE session rate grows. This is explained by the fact that the increase in L makes the system more deterministic by packing it with sources having minimum rate L. It is important that this trend is accompanied with increasing packet drop probability.

Analyzing the data illustrated in Fig. 8 further, one may notice that the effect of WiFi and LTE arrival rates on the mean number of LTE sessions offloaded onto LAA system is different. We illustrate this effect in detail in Fig. 9. As one may observe, both considered parameters increase the mean number of LTE sessions in the system. However, the effect of LTE arrival rate is much more profound. Particularly, as one may notice, when λ_L and λ_W reach 15 and 10, respectively, see Fig. 9a, there are two LTE sessions in the system on average. Contrarily, for $\lambda_L = 10$, $\lambda_W = 15$, the corresponding mean number of LTE sessions is just 1.4.

B. OFFLOADING ONTO WiFi

Having analyzed LTE sessions offloading onto LAA system, we now proceed addressing the case of offloading onto classic

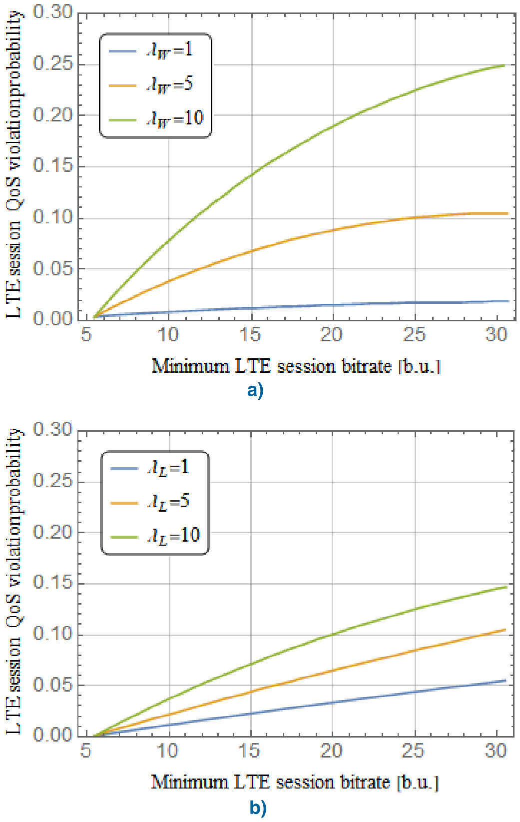

FIGURE 11. **Probability that the rate requirements are violated.**

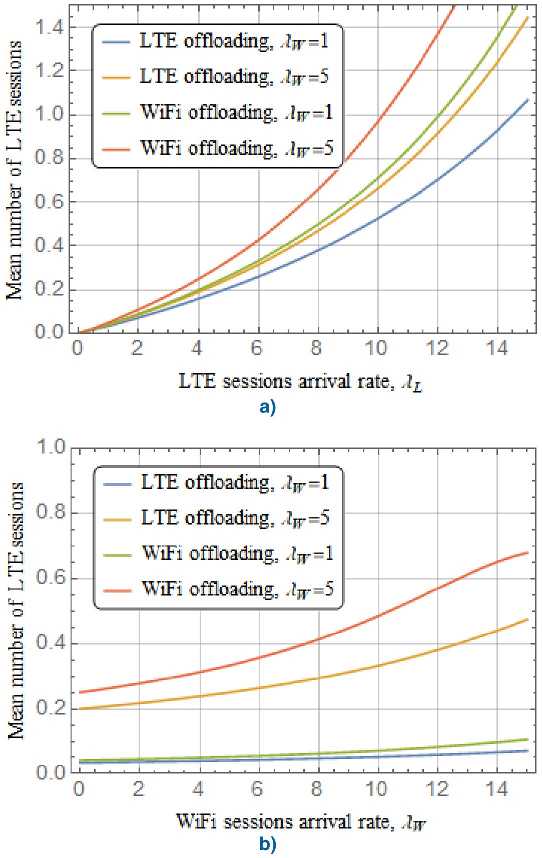

FIGURE 12. **Mean number of LTE sessions for our offloading schemes.**

Wi-Fi system. Fig. 10 shows the probability that the minimum LTE session rate requirements, L, are violated as a function of the LTE (Fig. 10a) or WiFi (Fig. 10b) session arrival rates. As one may observe, in both considered scenarios this probability increases. It is important to note that under high traffic conditions the service becomes unacceptable for both considered scenarios as a randomly chosen LTE session receives less throughput than requested approximately half of the time. Although the number of sessions in the system is definitely greater than in the case of LAA system (in fact, all LTE sessions are accepted) WiFi offloading scheme is only feasible under low traffic conditions.

Fig. 11 illustrates the probability that the minimum LTE session rate requirements, L, will be violated as a function of the minimum LTE session rate. Expectedly, as LTE sessions minimum bitrate requirements increase the probability of interest increases as well. However, once a certain rate is reached (approximately $L = 20$ b.u.) the probability plateaus and then remains irresponsive to further increase of L.

C. COMPARISON OF OFFLOADING STRATEGIES

We now directly compare the considered offloading strategies using the mean number of sessions in the system as a function of LTE sessions arrival rate and LTE sessions minimum bitrate requirements, illustrated in Fig. 12 for different LTE and WiFi session arrival rates. As one may observe, the number of offloaded sessions in WiFi offloading strategy is significantly greater compared to LAA system offloading drastically reducing the LTE network load. However, recalling the results of Fig. 10, this advantage comes at the expense of severe throughput guarantees violation.

VI. CONCLUSION

In this paper, we have developed a unified analytical framework for performance assessment of offloading of QoS-aware sessions from LTE BS onto WiFi AP and schedule-based LAA BS. The framework is based on queuing system with elastic traffic having minimum throughout requirements. Particularly, it allows to characterize a wide variety of relevant performance metrics for both considered offloading schemes including offloaded session drop probabilities, QoS violation probability mean number of offloaded sessions, etc.

Our numerical results show that WiFi offloading scheme is characterized by much large mean number of offloading sessions in the system. However, this advantage comes at the expense of severe QoS degradation. LAA offloading efficiently addresses this problem and keeps the number of interruptions of ongoing sessions at minimum. Thus, the use of LAA technology may provide performance guarantees in terms of minimum throughput.

The proposed model can be used for practical dimensioning of WiFi and LAA offloading schemes with elastic traffic complementing the model with CBR flows addressed in [20]. Particularly, the obtained results imply that the considered schedule-based LAA system may ensure nearly LTE-grade performance for a wide range of offered load conditions. In contrast, WiFi offloading may only provide QoS support in extremely light traffic conditions.

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