Analytical Study of License-Assisted Access in 5G Networks

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***Abstract*—The volume of traffic transmitted over cellular networks is growing significantly every year. To improve LTE network throughput, 3GPP has proposed License-Assisted Access (LTE-LAA), which allows utilizing the unlicensed 5GHz spectrum already used by Wi-Fi and other technologies. To enable fair resource sharing, LTE-LAA adopts CSMA/CA-based channel access with binary exponential backoff similar to Wi-Fi. However, because of the LTE-LAA technology constraints, the LTE-LAA base station may start data transmission only at rather rare licensed carrier slot boundaries. The essential question, what the base station should do between the end of the backoff procedure and the closest licensed slot boundary, is left implementation dependent. In the paper, we have developed analytical models to study the performance of different LTE-LAA implementations and analyze channel sharing fairness between LTE-LAA and Wi-Fi networks in the coexistence scenario. Moreover, we investigate how the performance of LTE-LAA channel access can be improved using New Radio flexible numerology, which is one of the main features of currently developed 5G systems.**

***Index Terms*—LTE-LAA, Wi-Fi, coexistence, fairness, 5G, flexible numerology, analytical modeling.**

I. INTRODUCTION

To meet raised demands for cellular networks throughput, it turns out inevitable to involve for transmission new frequency bands. Every new generation of cellular networks has increased user throughput in hundred times, but it seems that in 4G networks we have almost reached the physical limits of data rates which can be achieved in the traditional scarce and bandwidth-limited licensed spectrum. In comparison to higher frequencies, such as dozens of GHz or even higher, the usage of which has many technological and economic challenges, the shift towards unlicensed spectrum in well-studied 5 GHz bands is very attractive to both chipset vendors and mobile operators. It is not a surprise that there are many activities in 3GPP towards allowing cellular systems to use unlicensed spectrum.

The first notable step in this direction done by 3GPP consortium is the License-Assisted Access (LTE-LAA) technology introduced for LTE networks in 2016. LTE-LAA allows an LTE base station (BS) to transmit data in the unlicensed 5 GHz frequency band for traffic offloading, using the existing carrier aggregation framework.

Initially, in 3GPP LTE Release 13, the LTE-LAA specification has defined operation only for downlink data transmission, while all uplink data and control information shall be transmitted in licensed bands. Recently, in Release 14, the unlicensed uplink operation has been added as a part of so-called enhanced LAA (LTE-eLAA) technology [1]. However, since cellular traffic is significantly asymmetric and most of the data is transmitted in downlink [2], in this paper, we focus on LTE-LAA downlink performance only.

Unlike a licensed frequency band, which is used exclusively by the spectrum owner (e.g., by the mobile network operator), the unlicensed 5 GHz band has been already used by various wireless technologies, e.g., Wi-Fi, weather radars, etc. Because of that, LTE-LAA channel access mechanism for unlicensed spectrum has to take into account the existence of other technologies operating in the band. To access the channel in a fair and efficient way, the LTE-LAA technology includes several coexistence techniques, including dynamic frequency selection (DFS), transmit power control (TPC), listen before talk (LBT), etc. [1]

Since Wi-Fi devices working according to the IEEE 802.11a/n/ac/ax standard are the most widespread users of the unlicensed 5 GHz spectrum and therefore the main competitors for the band, let us first briefly describe the Wi-Fi channel access mechanism. According to the standard, Wi-Fi stations (STAs) use Enhanced Distributed Channel Access (EDCA) mechanism based on Carrier Sence Multiple Access with Collision Avoidance (CSMA/CA). In particular, before every transmission attempt, a Wi-Fi STA initializes the backoff counter with an integer number drawn from the interval $[0, W-1]$, where W is the current contention window. The STA decrements the backoff counter whenever the channel remains idle for slot σ. Otherwise, i.e., when the channel becomes busy, the backoff counter is suspended until the channel becomes idle again for interval $AIFS$. When the counter reaches zero, the Wi-Fi STA starts a transmission. If the transmission is successful, e.g., the STA receives an acknowledgment, the contention window W is reset to the minimal one equal to W_{min}. Otherwise, the STA repeats the backoff procedure with the doubled contention window W, but not larger than W_{max}. The standard defines four traffic types (access categories), each of them has different values of W_{min}, W_{max} and $AIFS$.

Apparently, when EDCA is used, collisions are inevitable. To decrease the collision duration, Wi-Fi STAs may use the RTS/CTS mechanism. In particular, when a STA's backoff

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counter reaches zero, before data transmission the STA transmits a short control frame RTS (Request-to-send). If the destination STA successfully receives RTS, it responds with a short CTS (Clear-to-send) frame. Having received the CTS, the originator STA sends a data frame. Despite introducing an overhead and increasing the duration of successful (non-collision) transmission attempt, RTS/CTS mechanism significantly reduces the collision duration and improves network throughput in scenarios with multiple STAs, hidden STAs, etc., since collisions involve only RTS frames.

LTE-LAA channel access mechanism called Listen-before-talk (LBT) has much in common with the Wi-Fi one. According to the 3GPP specification [3], LTE-LAA BS also implements CSMA/CA and performs the binary exponential backoff procedure with the same values of σ and $AIFS$, and with the same four access categories.

However, there are some important differences. First, at the time of writing the paper, there are no standardized methods reducing collision duration in the LTE-LAA specification. Second, by default, LTE-LAA uses longer transmissions than Wi-Fi does. Third, in Wi-Fi, a STA is ready to start frame reception almost at any moment. For that, every frame begins with a preamble allowing the receiver to detect the start of the Wi-Fi frame and synchronize itself with the transmitter. In legacy LTE, the time axis is divided into subframes of $1ms$, each of which contains two slots of duration $T = 500\mu s$. To distinguish these slots from the backoff slots, we will refer to these slots as licensed slots. Since LTE-LAA is just an extension of the legacy LTE, it also inherits the fixed channel time structure. Because of synchronization needed for the carrier aggregation framework, LTE-LAA transmissions in an unlicensed band may start only at the licensed slot boundaries. Since no preamble is used, LTE-LAA user equipment (UE) tries blindly detecting transmitted frames at these predefined time moments.

As can be noticed, because of the random nature of the backoff procedure, it may finish between licensed slot boundaries. The LTE-LAA specification leaves the behavior of the BS in such a situation implementation dependent, although it has a significant impact on both LTE-LAA and Wi-Fi performance.

In this paper, we investigate the performance of different LTE-LAA implementation options and estimate their fairness with respect to Wi-Fi. Usually, in this case, the fairness is defined as the property of an LTE-LAA device not to impact the performance of Wi-Fi devices more than an additional Wi-Fi device operating on the same channel [4].

Moreover, we study how the performance of LTE-LAA depends on the licensed slot T, i.e., the period of moments when an LTE-LAA BS may start data frame transmission. As previously mentioned, in the current specification of LTE-LAA, $T = 500\mu s$. However, in future releases describing 5G functionality, 3GPP is going to introduce a New Radio interface with flexible numerology. In particular, this feature will allow shortening the OFDM symbol duration, and, as a consequence, licensed slot duration T.

The rest of the paper is organized as follows. In Section II, we describe possible LTE-LAA implementation options related to the LTE-LAA BS behavior between the end of the backoff procedure and the closest licensed slot boundary. Section III provides the literature review. In Section IV, we describe the considered scenario and develop analytical models for different LTE-LAA implementations. Section V contains numerical results and the analysis of the channel resource sharing fairness. Section VI concludes the paper and lists directions for future work.

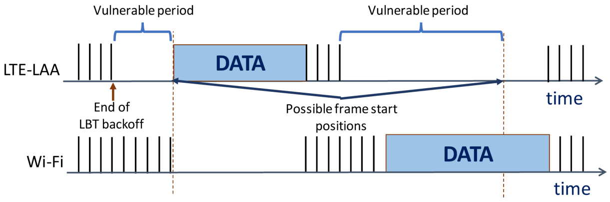

Figure 1. LTE-LAA implementation without reservation signal

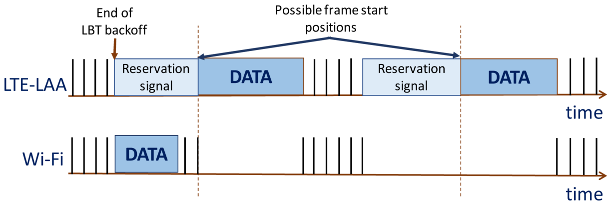

Figure 2. LTE-LAA implementation with reservation signal

II. LTE-LAA IMPLEMENTATION OPTIONS

In this Section, we describe possible LTE-LAA implementation options regarding the BS behavior during the interval between the end of the backoff procedure and the closest licensed slot boundary. Further, we refer to this interval as a vulnerable interval.

The first possible implementation option for the LTE-LAA BS is to stay silent during the vulnerable interval, see Fig. 1. In this case, if the channel is idle for more than $AIFS$ immediately before the licensed slot boundary, the LTE-LAA BS starts data transmission at the boundary. Otherwise, if the channel turns out to be busy, the LTE-LAA BS has to repeat the backoff procedure using the same contention window value. Naturally, since any Wi-Fi STA may start transmission during the vulnerable interval, such behavior may lead to poor LTE-LAA performance, especially when the number of active Wi-Fi STAs is high.

The second implementation option considered in the majority of papers [4]–[8] is to send the blocking energy (reservation signal) during the vulnerable interval to forbid Wi-Fi STAs to occupy the channel, see Fig. 2. Although this approach is straightforward, it draws many problems. First, much airtime is wasted on transmitting a signal which does not carry any control or user data. Second, if Wi-Fi STAs using the RTS/CTS mechanism coexist with LTE-LAA BSs, their collisions appear to be asymmetric when the RTS frame duration is smaller than the reservation signal one. In this case, the Wi-Fi RTS originator STA detects the collision and refuses from data transmission, but the LTE-LAA BS data following the reservation signal is left unaffected. Thus, the LTE-LAA BS does not detect the collision. As a consequence, Wi-Fi throughput significantly decreases.

III. RELATED PAPERS

The efficiency of the LTE-LAA channel access is studied in a number of papers both in scenarios with only LTE-LAA BSs [5], [6] and in LTE-LAA/Wi-Fi coexistence scenarios [4], [7]–[9].

In [5], authors compare the performance of the LTE-LAA implementation with reservation signal and the implementation without frame start position constraints, i.e., when an LTE BS may begin transmission in arbitrary moments of time. By means of simulation, it has been shown that the second implementation provides up to 40% higher throughput. Apart from that, the authors propose a frequency reuse scheme and show that it can significantly improve LTE-LAA performance. Unfortunately, in [5], the coexistence of only LTE-LAA BSs are considered, and it is not clear whether the proposed frequency reuse scheme allows achieving similar results for coexisting with Wi-Fi STAs.

In [6], an analytical model is developed for the LTE-LAA throughput evaluation in the scenario with only LTE-LAA BSs. The authors consider that all the BSs use the reservation signal and take into account the induced overhead. Unfortunately, the authors do not consider the LTE-LAA coexistence with Wi-Fi STAs and LTE-LAA performance without reservation signal.

In [4], the authors develop an LTE-LAA module for network simulator ns-3 and study LTE-LAA performance in the unsaturated coexistence scenario. It has been shown that in the considered scenario, LTE-LAA implementation with reservation signal shows better performance than Wi-Fi in terms of throughput, but leads to the throughput degradation for Wi-Fi STAs. However, the authors do not consider LTE-LAA implementation without a reservation signal.

An oversimplified analytical model which allows evaluating the network performance of LTE-LAA BSs and Wi-Fi STAs in a coexistence scenario is presented in [7]. The authors consider saturated conditions and LTE-LAA implementation with reservation signal and contention window of a fixed size. The developed model allows finding the optimal contention window at the LTE-LAA BS using the exhaustive search. However, the overhead imposed by reservation signal as well as other implementations of LTE-LAA, e.g., with variable contention window size (which is used by default in the LTE-LAA specification) or without reservation signal, are left out of the scope of this paper.

Coexistence of Wi-Fi and LTE-LAA networks in the unsaturated scenario is considered in [8]. The authors of this paper use simulation to compare various approaches to achieve fair coexistence between considered networks, including different values of energy detection thresholds, different LAA transmission durations, LTE-LAA implementations with and without reservation signal. According to the achieved results, the most promising of the considered solutions is to limit the reservation signal duration by 3 OFDM symbols ($\approx 215 \mu s$).

The authors of [10] consider two approaches to the unlicensed spectrum access: Carrier Sense Adaptive Transmission (CSAT) and LBT. They conclude that the approaches are equally fair for the system of the LTE-LAA BS and Wi-Fi STAs for long LTE-LAA transmission duration (50 ms). For short duration (10 ms), LBT shows better performance for the LTE-LAA BS.

A reservation signal use and hybrid approaches to the LTE-LAA BS channel access are presented in [11]. Authors conclude that reservation signal use makes the coexistence between LTE-LAA and Wi-Fi STAs unfair, so, they propose to implement a hybrid channel access, where the LTE-LAA has a "sleep" period at the beginning of every licensed spectrum slot during the backoff counting, thus reducing the overhead caused by reservation signal use.

In [12], the authors consider another technology for unlicensed spectrum, namely LTE-U, which does not use LBT, or uses asynchronous or synchronous LBT (consequently uses reservation signal). The simulation shows that LBT makes both cellular and Wi-Fi devices coexist more effectively, in particular, with asynchronous LBT. However, this approach is not included in existed 3GPP specifications. The authors also conclude that all the methods show worse Wi-Fi STAs throughput than that in only Wi-Fi STAs scenario, which means that they are unfair for Wi-Fi.

In all the considered papers, mostly LTE-LAA implementation with reservation signal is examined, whereas LTE-LAA without reservation signal is not investigated well enough. In this paper, we analyze the performance of coexisting LTE-LAA and Wi-Fi networks, taking into account both LTE-LAA implementation options, see Section II. Moreover, we consider different periodicity of time moments when an LTE-LAA BS may start data transmission in the unlicensed spectrum. The latter will be possible in future 5G networks thanks to the flexible numerology of NR.

IV. ANALYTICAL MODELS

Consider a scenario with N Wi-Fi STAs and one LTE-LAA BS transmitting data to some UE. BS and all the STAs works in saturation, i.e., they always have packets for transmission. Besides, all devices are in the radio transmission range of each other. We assume that either all the Wi-Fi STAs use RTS/CTS mechanism or none of them use it.

We assume that the LTE-LAA transmission is longer than the Wi-Fi one. Since an LTE-LAA transmission consists of several frames which are decoded independently, in case of collision with a short Wi-Fi frame, the tail of LTE-LAA transmission unaffected by the collision is assumed to be decoded successfully. Moreover, we take into account that in LTE-LAA, contention window W is increased only if the first data frame of the transmission is corrupted by the collision.

Apart from that, we assume that the duration of the vulnerable interval $\tilde{T}$ is uniformly distributed on the interval $[0, T)$. Also, we consider that all the data transmissions of Wi-Fi have the same duration.

A. LTE-LAA Implementation with Reservation Signal

Since the values of σ and $AIFS$ are the same for Wi-Fi and LTE-LAA, when we use LTE-LAA implementation with reservation signal, backoff counters of the LTE-LAA BS and Wi-Fi STAs change at the same time instances. Because of that, it is possible to use Bianchi's virtual slot-based approach proposed in [13]. According to [13], the virtual slot is an interval between two sequential countdowns of the backoff counter. To find throughput S_W (or, similarly, S_L) of all Wi-Fi STAs (the LTE-LAA BS), we evaluate the probability p_s^W (p_s^L) of the successful Wi-Fi STA (LTE-LAA BS) virtual slot and the probability p_c^{LW} of the collision involving frames of the LTE-LAA BS and at least one Wi-Fi STA. Besides, we evaluate the average virtual slot duration T_{slot}.

Then, throughputs of Wi-Fi and LTE-LAA networks can be found as follows:

$$S_L = \frac{\left(p_s^L + p_c^{LW} \frac{T^L - \max(\frac{T}{2}, T_c^W)}{T^L - \frac{T}{2}}\right) d_L}{T_{slot}},$$

$$S_W = \frac{p_s^W d_W}{T_{slot}},$$

where T^L is the average duration of the LTE-LAA transmission including the reservation signal with the average duration of $\frac{T}{2}$, T_c^W is the duration of the collided Wi-Fi transmission, d_L (d_W) is the average amount of data in an LTE-LAA (Wi-Fi) transmission. Note that the whole amount of data d_L is transmitted by the LTE-LAA BS during an interval of duration $T^L - \frac{T}{2}$. If a collision between the LTE-LAA BS and a Wi-Fi STA happens and the duration of LTE-LAA reservation signal is smaller than T_c^W, the LTE-LAA BS receives only the unharmed tail of frame with the duration $T^L - T_c^W$.

Similar to [13], let us introduce the probability τ_W (τ_L) of choosing the current slot for transmission by a given Wi-Fi STA (LTE-LAA BS).

If a given Wi-Fi STA has chosen the current slot for transmission, collision occurs with the probability ρ_c^W, if at least one more device chooses the same slot:

$$\rho_c^W = 1 - (1 - \tau_L)(1 - \tau_W)^{N-1}. \qquad (1)$$

As for the LTE-LAA BS, if it has chosen the current slot for transmission, it detects the collision with the probability ρ_c^L, if at least one Wi-Fi STA chooses the same slot and the duration of Wi-Fi transmission during the collision is higher than the duration of the vulnerable interval:

$$\rho_c^L = \left(1 - (1 - \tau_W)^N\right) \frac{\min(T_c^W, T)}{T}. \qquad (2)$$

The probabilities τ_W (τ_L) can be found by calculating how many virtual slots in average a Wi-Fi STA (LTE-LAA BS) counts to perform one transmission attempt:

$$\tau_W = \frac{1}{1 + \frac{W_{min}^W - 1}{2} + \rho_c^W \cdot \frac{W_{min}^W}{2} \sum\limits_{i=0}^{m^W - 1} (2\rho_c^W)^i}, \qquad (3)$$

$$\tau_L = \frac{1}{1 + \frac{W_{min}^L - 1}{2} + \rho_c^L \cdot \frac{W_{min}^L}{2} \sum\limits_{i=0}^{m^L - 1} (2\rho_c^L)^i}, \qquad (4)$$

where

$$m = \log_2\left(\frac{W_{max}}{W_{min}}\right).$$

Having solved the system (1)-(4), we find the sought probabilities τ_W and τ_L.

Let us find the probability p_e that a given virtual slot is idle. It happens if neither any of N Wi-Fi STAs nor LTE-LAA BS chooses the virtual slot for transmission:

$$p_e = (1 - \tau_L)(1 - \tau_W)^N.$$

One of the Wi-Fi STAs (LTE-LAA BS) successfully transmits in the current virtual slot with probability p_s^W (p_s^L), if it chooses this slot for transmission, but the rest of the devices do not:

$$p_s^W = N\tau_W(1 - \tau_L)(1 - \tau_W)^{N-1},$$

$$p_s^L = \tau_L(1 - \tau_W)^N.$$

Let us find the probability p_c^W of a collision involving only Wi-Fi STAs:

$$p_c^W = (1 - \tau_L)(1 - (1 - \tau_W)^N - N\tau_W(1 - \tau_W)^{N-1}).$$

Then the average duration T_{slot} of a virtual slot can be found as follows:

$$T_{slot} = p_e\sigma + p_s^W T_s^W + (p_s^L + p_c^{LW})T^L + (T_c^W + AIFS)p_c^W,$$

where T_s^W is the average duration of the successful Wi-Fi STA transmission and

$$p_c^{LW} = 1 - p_e - p_s^W - p_s^L - p_c^W.$$

B. LTE-LAA Implementation without Reservation Signal

Since during the vulnerable interval only Wi-Fi STAs count their backoffs, the approach described in [13] is not suitable. Instead of this, to analyze LTE-LAA and Wi-Fi performance, we use the approach similar to [14]. In particular, to find Wi-Fi (LTE-LAA) throughput, let us evaluate the average duration E_W (E_L) of the interval between endings of two sequential successful transmissions of a Wi-Fi STA (LTE-LAA BS). Then the throughput can be expressed as follows:

$$S = \frac{d}{E}.$$

In our model, we consider ideal channel sensing, i.e., the time needed to switch between RX and TX is much smaller than the backoff slot duration σ, and a Wi-Fi STA (LTE-LAA BS) almost instantly detects that the channel becomes busy. Because of that, similar to [15], we neglect the probability of a collision involving LTE-LAA and Wi-Fi frames, since the coincidence of the licensed spectrum slot boundaries and the Wi-Fi backoff slot boundaries is unlikely.

Similar to [14], in this Section, we redefine the term "virtual slot" which is now the interval between two sequential countdowns of the backoff counter of the given Wi-Fi STA (LTE-LAA BS), provided that it does not transmit during this interval.

Having finished the backoff procedure, the LTE-LAA BS waits for the closest licensed spectrum slot boundary, i.e., the vulnerable interval begins, see Fig. 1. Let ρ_c^L be the probability of the LTE-LAA BS access failure, which occurs when the BS founds the channel busy at the end of the vulnerable period. Note that in this case, LTE-LAA BS has to postpone the data transmission and repeat the backoff procedure with the same contention window W value.

Let a_i^W (a_i^L) be the duration of the transmission attempt $i+1$ of a Wi-Fi STA (LTE-LAA BS). It consists of the backoff procedure, the transmission itself, and the vulnerable interval in case of LTE-LAA BS. Then the average duration of the interval between endings of the two sequential successful transmissions can be found as follows:

$$E = a_0 + \sum_{i=1}^{\infty} a_i (\rho_c)^i. \tag{5}$$

First, let us evaluate the throughput of a Wi-Fi STA.

The duration of the transmission attempt $(i+1)$ can be found as following:

$$a_i^W = \frac{W_i^W - 1}{2} t_{slot}^W + (1-\tau_W)^{N-1} T_s^W + (1-(1-\tau_W)^{N-1}) T_c^W,$$

where t_{slot}^W is the average duration of the virtual slot for the Wi-Fi STA. This virtual slot can be empty, busy with the transmission or the collision of other Wi-Fi STAs or busy with the LTE-LAA BS transmission. Probability $\tilde{p}$ that the LTE-LAA BS completes the backoff procedure, and no one of Wi-Fi STAs has started the transmission during the vulnerable interval, which leads to the LTE-LAA BS channel access failure, can be found as:

$$\tilde{p} = \tau_L (1 - \rho_c^L).$$

As a collision between LTE-LAA BS and Wi-Fi devices is unlikely, LTE-LAA contention window is constant and τ_L can be found as following:

$$\tau_L = \frac{2}{W_{min}^L + 1}.$$

As a result, the average duraion t_{slot}^W of the Wi-Fi STA virtual slot can be found as:

$$\begin{aligned} t_{slot}^W &= (1-\tau_W)^{N-1}(1-\tilde{p})\sigma + (1-\tau_W)^{N-1}\tilde{p} T_s^L + \\ &+ (N-1)\tau_W (1-\tau_W)^{N-2} T_s^W + \\ &+ (1-(N-1)\tau_W(1-\tau_W)^{N-2} - (1-\tau_W)^{N-1}) T_c^W. \end{aligned}$$

If a given Wi-Fi STA has chosen the current slot for transmission, a collision happens with probability ρ_c^W, if at least one more Wi-Fi STA chooses this slot too:

$$\rho_c^W = 1 - (1-\tau_W)^{N-1}. \tag{6}$$

The probability τ_W of choosing the current slot for transmission by a Wi-Fi STA can be found using (3).

Using a similar approach, let us evaluate the throughput of the LTE-LAA BS.

LTE-LAA BS transmission attempt consists of the number of the virtual slots and the part of the vulnerable interval, which ends with the successful LTE-LAA BS transmission of the duration T^L or with a Wi-Fi transmission of the average duration T^W, which makes the LTE-LAA BS access attempt failed. Corresponding average durations of the vulnerable interval are V_s and V_c.

The vulnerable interval ends with the Wi-Fi STA successful or collision virtual slot with the probability ρ_c^L or with successful LTE-LAA BS transmission with the probability $(1-\rho_c^L)$. Then a_i^L can be found as:

$$a_i^L = \frac{W_{min}^L - 1}{2} t_{slot}^L + \rho_c^L (V_c + T^W) + (1-\rho_c^L)(V_s + T^L), \tag{7}$$

where t_{slot}^L is the average duration of the LTE-LAA BS virtual slot.

LTE-LAA BS virtual slot can be empty, successful for one of Wi-Fi STAs or unsuccessful:

$$\begin{aligned} t_{slot}^L &= (1-\tau_W)^N \sigma + N\tau_W (1-\tau_W)^{N-1} T_s^W + \\ &+ (1-(1-\tau_W)^N - N\tau_W(1-\tau_W)^{N-1}) T_c^W. \end{aligned}$$

To find the probability ρ_c^L, we use the stationary distribution of Wi-Fi STA backoff counter value found in [13]. In particular, the stationary probability $b_{i,k}$ of being in the state with $W = 2^i W_{min}^W$ and with current backoff counter k can be found as follows:

$$b_{i,k} = \begin{cases} b_{0,0} \frac{W_{min}^W 2^i - k}{W_{min}^W 2^i} (\rho_c^W)^i, & k < W_{min}^W 2^i \\ 0, & \text{otherwise}, \end{cases} \tag{8}$$

where

$$b_{0,0} = \frac{2(1-2\rho_c^W)(1-\rho_c^W)}{(1-2\rho_c^W)(W_{min}^W + 1) + pW_{min}^W (1-(2\rho_c^W)^m)}. \tag{9}$$

Then the probability t_f that the backoff counter of a given Wi-Fi STA equals f can found as follows:

$$t_f = \sum_{i=0}^{m} b_{i,f}.$$

The probability s_f that the backoff counter of the given Wi-Fi STA is less than f is expressed as:

$$s_f = \sum_{i=0}^{m} \sum_{k=0}^{f-1} b_{i,k}.$$

Back to ρ_c^L, the LTE-LAA BS starts data transmission at the end of the vulnerable period under one of the following conditions. The first one is that none of the Wi-Fi STAs starts the transmission during the vulnerable interval, i.e., if the current backoff counter values of all Wi-Fi STAs are not less than $\tilde{T}$ expressed as the integer number f of slots σ. This condition is satisfied with probability $(1-s_{f-1})^N$. The second condition is that the collision of Wi-Fi STAs during the vulnerable interval ends before the beginning of the LTE-LAA transmission. It happens, if the current backoff counter values of two Wi-Fi STAs (we do not consider the collision of three or more Wi-Fi STAs here) are equal to k and less than $\tilde{T}-T_c^W$ (with probability $\binom{N}{2}t_{k-1}^2$), their new backoff counter values (after the collision) are not less the remaining part of $\tilde{T}$ (with the probability $(1-s_{f-k-C})^2$) and the backoff counters of the rest of Wi-Fi STAs have values not less than $\tilde{T}-T_c^W$ (this happens with probability $(1-s_{f-C})^{N-2}$, where $C=\lfloor\frac{T_c^W}{\sigma}\rfloor$). Note that the success of the LTE-LAA BS transmission after a collision is possible if $T>T_c^W$. As a result, we obtain:

$$\rho_c^L = 1-\sum_{f=1}^{P}\frac{\sigma}{T}\Bigg((1-s_{f-1})^N+$$
$$+\mathbb{1}(T>T_c^W)\big(\sum_{k=0}^{f-C}((\tbinom{N}{2})t_{k-1}^2(1-s_{f-C})^{N-2}(1-s_{f-k-C})^2)\Bigg),$$

where $P=\lfloor\frac{T}{\sigma}\rfloor$, $\mathbb{1}(T>T_c^W)$ indicates that the duration of Wi-Fi STA collision is less than T:

$$\mathbb{1}(T>T_c^W)=\begin{cases}1, & T>T_c^W\\ 0, & \text{otherwise.}\end{cases}$$

Now let us evaluate V_s. There are two cases when LTE-LAA BS successfully starts transmission: when no one of Wi-Fi STAs starts transmission during the vulnerable interval (with probability $\xi_{s,1}$) or there is a collision of Wi-Fi STAs which does not harm the LTE-LAA BS transmission if $T>T_c^W$ (with probability $\xi_{s,2}$).

Then V_s can be found as:

$$V_s=\frac{\xi_{s,1}V_{s,1}+\xi_{s,2}V_{s,2}}{\xi_{s,1}+\xi_{s,2}}.$$

where $V_{s,1}$ and $V_{s,2}$ are the relevant average durations of the vulnerable interval, which ends with the successful LTE-LAA BS transmission for the both cases.

All the Wi-Fi STAs do not start their transmission during the vulnerable period having duration $f\sigma$, if each STA does not choose any of f sequential virtual slots for transmission:

$$\xi_{s,1}=\sum_{f=1}^{P}\frac{\sigma}{T}(1-\tau_W)^{(f+1)N},$$

$$V_{s,1}=\sum_{f=1}^{P}\frac{\sigma}{T}f\sigma(1-\tau_W)^{(f+1)N}.$$

To estimate $\xi_{s,2}$, we found probability $(1-\tau_W)^{(i-C)N}$ that none of the Wi-Fi STAs starts transmission during the remaining part of the vulnerable interval of the length $i\sigma$ after a collision of duration $C\sigma$. Then, $\xi_{s,2}$ can be found as:

$$\xi_{s,2}=\sum_{i=C}^{P}\frac{\sigma}{T}(1-\tau_W)^{(i-C)N}(1-(1-\tau_W)^N-$$
$$-N\tau_W(1-\tau_W)^{N-1}),$$

Substituting the value of the transmission duration and performing averaging, we obtain:

$$V_{s,2}=\sum_{i=C}^{P}\frac{\sigma}{T}((i-C)\sigma+T_c^W)(1-\tau_W)^{(i-C)N}\cdot$$
$$\cdot(1-(1-\tau_W)^N-N\tau_W(1-\tau_W)^{N-1}).$$

Now let us find V_c. LTE-LAA BS access failure can occur with probability $\xi_{c,1}$ if (i) Wi-Fi STAs collision occurs during the vulnerable interval, but it does not harm the LTE-LAA BS transmission (when $T>T_c^W$), (ii) then some of Wi-Fi STAs start transmission during the vulnerable interval what leads to the LTE-LAA BS access failure. Also, only one Wi-Fi STA starts transmission during the vulnerable interval, and LTE-LAA BS, therefore, finds the channel busy at the end of the vulnerable period and repeats the backoff procedure with probability ξ_c^2. ξ_c^3 is the probability that a collision of Wi-Fi STAs leads to the LTE-LAA BS access failure. Corresponding average durations of the vulnerable interval are $V_{c,1}$, $V_{c,2}$ and $V_{c,3}$. Then V_c is expressed as:

$$V_c=\frac{\mathbb{1}(T>T_c^W)\xi_{c,1}V_{c,1}+\xi_{c,2}V_{c,2}+\xi_{c,3}V_{c,3}}{\mathbb{1}(T>T_c^W)\xi_{c,1}+\xi_{c,2}+\xi_{c,3}}.$$

As a result, we can explisitly determine T^W in (7):

$$\rho_c^L T^W=\xi_{c,3}T_c^W+(\mathbb{1}(T>T_c^W)\xi_{c,1}+\xi_{c,2})T_s^W.$$

The probability $\xi_{c,1}$ that no one of Wi-Fi STAs starts transmission during the interval of duration $j\sigma<\tilde{T}-T_c^W$, then a collision occurs, and some of Wi-Fi STAs starts transmission during the remaining part of $\tilde{T}$ can be found as:

$$\xi_{c,1}=\sum_{i=C}^{P}\sum_{j=0}^{i-C}\frac{\sigma}{T}(1-\tau_W)^{jN}(1-(1-\tau_W)^N-$$
$$-N\tau_W(1-\tau_W)^{N-1})(1-(1-\tau_W)^{i-j-C}).$$

As the interval $V_{c,1}$ consists several empty slots before the collision, the collision, and several empty slots before a Wi-Fi STA transmission, we obtain:

$$V_{c,1}=\sum_{i=C}^{P}\sum_{j=0}^{i-C}\frac{\sigma}{T}\frac{\sum\limits_{k=0}^{i-j-C}((j+k)\sigma+T_c^W)(1-\tau_W)^{(j+k+1)N-1}}{\sum\limits_{k=0}^{i-j-C}(1-\tau_W)^{(j+k+1)N-1}}.$$

If only one of N Wi-Fi STAs starts transmission at some point of the vulnerable period and the rest of them are silent, the corresponding probability and duration can be found as:

$$\xi_{c,2}=\sum_{i=0}^{P}\sum_{j=0}^{i}\frac{\sigma}{T}(1-\tau_W)^{(j+1)N-1}N\tau_W,$$

$$V_{c,2}=\sum_{i=0}^{P}\frac{\sigma}{T}\frac{\sum_{j=0}^{i}j\sigma(1-\tau_W)^{(j+1)N-1}}{\sum_{j=0}^{i}(1-\tau_W)^{(j+1)N-1}}.$$

If there are $j\sigma>\tilde{T}-T_c^W$ empty slots and then a Wi-Fi collision occurs, LTE-LAA BS access is also failed. The corresponding probability $\xi_{c,3}$ and the average duration $V_{c,3}$ are:

Table I
TRANSMISSION PARAMETERS

T_s^W	$5ms$ / $2.5ms$	
T_c^W	$5ms$/ $2.5ms$, w/o RTS/CTS	$86\mu s$, with RTS/CTS
W_{min}	16	
W_{max}	1024	
T^L	$8ms$	
W^L_{min}	16	
W^L_{max}	1024	

$$\xi_{c,3} = \sum_{i=0}^{P} \sum_{j=\max(0,i-C)}^{i} \frac{\sigma}{T}(1-\tau_W)^{jN}(1-(1-\tau_W)^N - \\ - N\tau_W(1-\tau_W)^{(N-1)}),$$

$$V_{c,3} = \sum_{i=0}^{P} \frac{\sigma}{T} \frac{\sum\limits_{j=\max(0,i-C)}^{i} (\max(i-C,0)+j)\sigma(1-\tau_W)^{jN}}{\sum\limits_{j=\max(0,i-C)}^{i} (1-\tau_W)^{jN}}.$$

Substituting the found values of a_i^L and a_i^W into (5), we find the throughputs S_W and S_L.

V. NUMERICAL RESULTS

To analyze the fairness and efficiency of Wi-Fi and LTE-LAA coexistence, we compare the performance in two scenarios. In the reference scenario, $N+1$ Wi-Fi STAs transmit saturated traffic to some receiver(s). In the coexistence scenario, one of the STAs is replaced with an LTE-LAA BS which sends data to some UE. In other words, there are N transmitting Wi-Fi STAs and 1 transmitting LTE-LAA BS. In both scenarios, all the devices are in the transmission range of each other.

Let S_W^1 be the Wi-Fi STA throughput in the reference scenario, and S_W^2 and S_L^2 be the throughputs of Wi-Fi STAs and LTE-LAA BS in the coexistence scenario, respectively.

We consider two key performance indicators (KPIs). The first one is the gain in the throughput of a Wi-Fi STA calculated as follows:

$$G_W = \frac{S_W^2 - S_W^1}{S_W^1}.$$

The second KPI is the gain G_L in the throughput of the LTE-LAA BS with respect to the throughput of the replaced Wi-Fi STA. Since all the Wi-Fi STAs equally share the channel, G_L is calculated as follows:

$$G_L = \frac{S_L^2 - S_W^1}{S_W^1}.$$

As mentioned before, LTE-LAA channel access is assumed fair if it affects Wi-Fi STAs not more than an additional Wi-Fi STA, i.e., when $G_W > 0$. At the same time, LTE-LAA outperforms Wi-Fi technology in terms of throughput if $G_L > 0$. Summing up, the implementation of LTE-LAA is both fair and efficient if both the gains are positive.

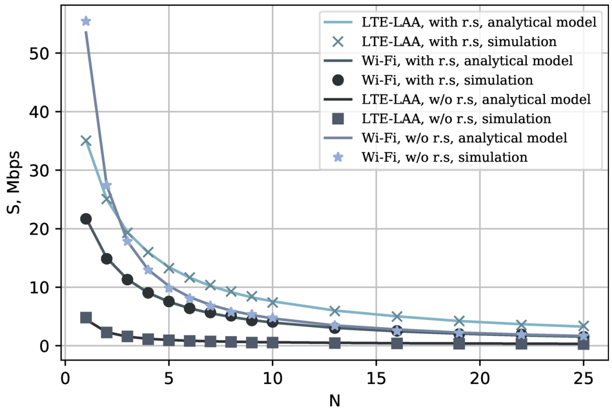

Figure 3. Analytical model validation for $T = 500\mu s$ and $T_s^W = 5ms$

We study the fairness and efficiency of the considered LTE-LAA implementations with different numbers of Wi-Fi STAs and different values of licensed slot duration T. If otherwise is not stated, we use the parameters for LTE-LAA and Wi-Fi transmissions from Table I. The numerical values in Table I correspond to the best effort traffic in both the Wi-Fi standard and the LTE-LAA specification. Moreover, the transmission durations equal to the maximum allowed values. We also suppose that the LTE-LAA BS and all the Wi-Fi STAs use the same 20 MHz channel at 5 GHz. Apart from that, we consider that in both technologies, the devices use the fastest available in the standard modulation and coding scheme. Firstly, we have validated the developed analytical model using simulation, see Fig. 3. In simulation, we also assume ideal channel sensing. It should be noted that in all the considered cases the relative error provided by the analytical model is below 5%.

Fig. 4 presents the numerical results for the case, when the duration of Wi-Fi transmissions is equal to $T_s^W = 5ms$. In this case, the LTE-LAA implementation with reservation signal (the curves are marked with “r. s.”) turns out to be unfair, no matter if Wi-Fi collisions are long (without RTS/CTS) or short (with RTS/CTS). In particular, the manifold gain in throughput for the LTE-LAA BS comes jointly with significant Wi-Fi throughput degradation. The reason for the higher performance of LTE-LAA is the higher transmission duration T^L.

The LTE-LAA implementation without reservation signal is fair with regard to Wi-Fi STAs, but the LTE-LAA BS has a positive gain only when $T < 100\mu s$ and when the number of Wi-Fi STAs is great ($N > 10$). Replacing a Wi-Fi STA with an LTE-LAA BS can be fruitful since in this case, collisions between LTE-LAA and Wi-Fi transmissions are hardly possible (see above) and the LTE-LAA transmission has higher duration and thus lower overhead.

However, with high T, the LTE-LAA BS rarely access the channel because Wi-Fi devices start their transmissions during the vulnerable interval, what forces LTE-LAA BS to restart the backoff procedure. When the number of Wi-Fi STAs N increases, collision probability for Wi-Fi transmissions

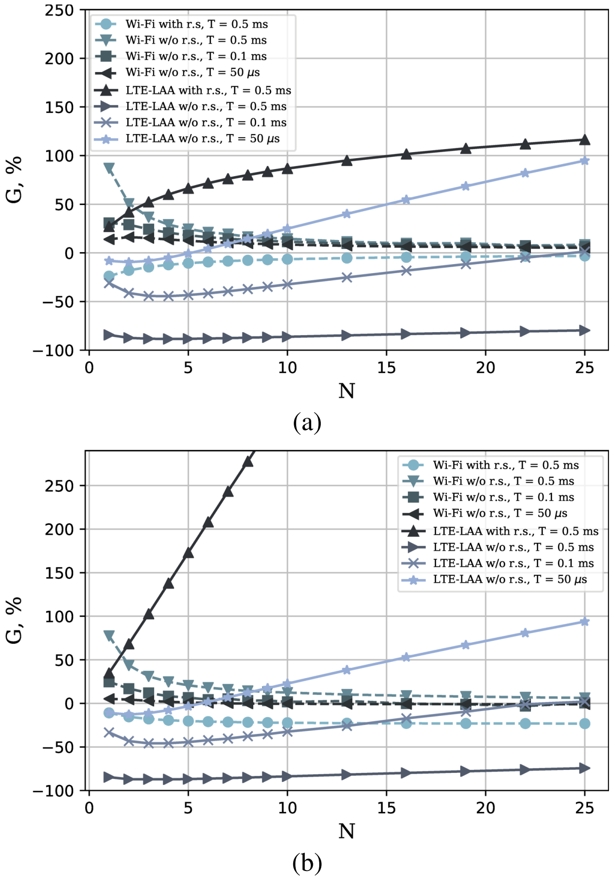

Figure 4. Throughput gains for Wi-Fi and LTE-LAA vs. the number of Wi-Fi STAs for the Wi-Fi transmission duration of $T_s^W = 5ms$ a) without RTS/CTS b) with RTS/CTS

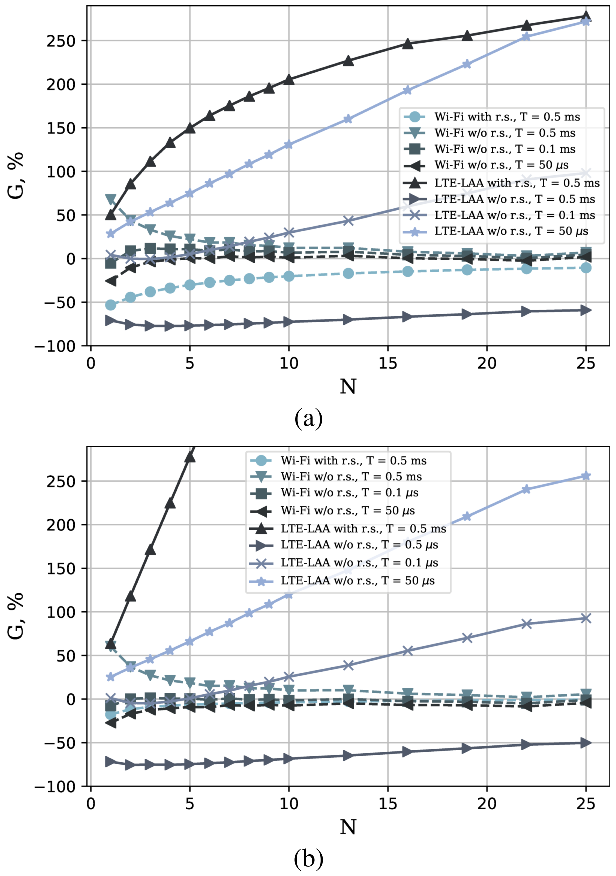

Figure 5. Throughput gains for Wi-Fi and LTE-LAA vs. the number of Wi-Fi STAs for the Wi-Fi transmission duration of $T_s^W = 2.5ms$ a) without RTS/CTS b) with RTS/CTS

becomes high, while LTE-LAA transmissions do not suffer from the collisions with Wi-Fi STAs. If Wi-Fi collisions are short, i.e., when the RTS/CTS mechanism is used, the gain in LTE-LAA throughput is slightly greater because during the vulnerable interval a Wi-Fi transmission does not necessarily cause channel access failure of the LTE-LAA BS.

When the Wi-Fi transmission duration equals $T_s^W = 2.5ms$ (see Fig. 5), the results for LTE-LAA BS are similar to the previous ones, but the fair coexistence can be achieved with higher values of T. This happens because Wi-Fi transmissions become much shorter than LTE ones. This effect is even more notable if RTS/CTS is used.

With the developed model, we have analyzed the performance of LTE-LAA without reservation signal and estimated the minimal (T_{min}) and the maximal (T_{max}) values of the licensed slot duration under the condition that both LTE-LAA and Wi-Fi gains are non-negative, see Figs. 6-7. In all the considered cases, T_{max} corresponds to the case when G_W is maximal, and G_L is zero, while T_{min} corresponds to the opposite situation. When $T_{min} < T < T_{max}$, both networks achieve positive gain, while in all the other cases at least one of the gains is negative. It should be noticed that if the number of Wi-Fi STAs is small, sometimes fair and efficient coexistence cannot be achieved with any T, e.g., when $N = 1$, $T_s^W = 5$ and RTS/CTS is not used.

In practice, we are interested in achieving the fair coexistence with greater values of T, since the higher is T, the lower is the complexity of LTE-LAA devices. Because of that, we decrease minimum contention window W_{min}^L of LTE-LAA to 2, see Fig. 7.

It is also clear that the values of T which are fair for some number of STAs N are also fair for the greater number of STAs. Thus, it is possible to set T value, which would provide fairness regardless of the number of Wi-Fi STAs N.

Since the LTE-LAA gain shows the maximum value when $T = T_{min}$, Fig. 8 represents the gains for LTE-LAA, corresponding to the several curves T_{min} on Figs. 6-7.

Note that with the smaller contention window W_{min}^L the LTE-LAA BS gets an advantage in the channel access compared with Wi-Fi STAs, which results in the higher T_{min} in Fig. 7 comparing to Fig. 6 and the greater probability of the LTE-LAA vulnerable period ending with Wi-Fi transmission. Since LTE-LAA performance is severely affected by these access failures, the gain for LTE-LAA is higher when its contention window is greater (see Fig. 8).

T_{min} and T_{max} values are also greater when $T_s^W = 2.5ms$ compared with $T_s^W = 5ms$ (see Fig. 6), as LTE-LAA gets more airtime compared with Wi-Fi. Since the effects of greater LTE-LAA transmission duration and the higher probability of the LTE-LAA channel access failure compensate each other, there is no noticeable difference between maximum LTE-LAA gains for these cases (see Fig. 8).

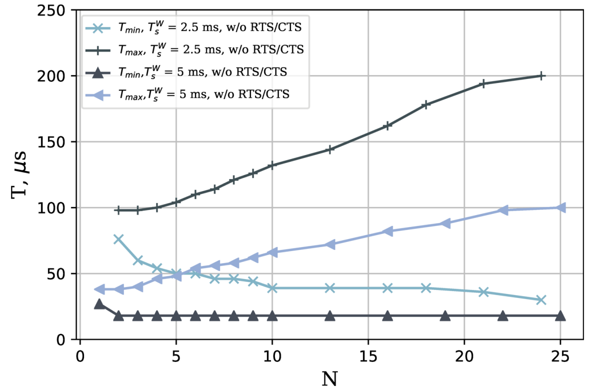

Figure 6. Maximum and minimum T for which the gains in Wi-Fi and LTE-LAA throughputs are positive for $W^L_{min} = 16$ vs. the number of Wi-Fi STAs

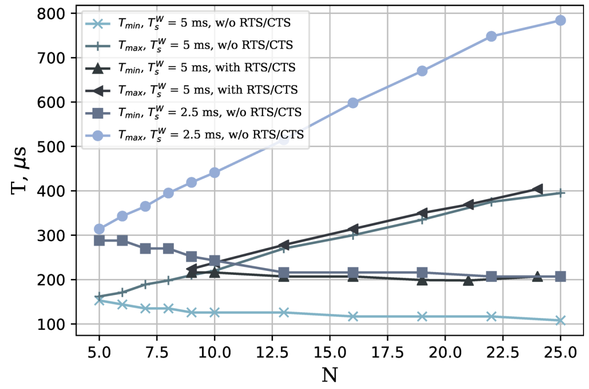

Figure 7. Maximum and minimum T for which Wi-Fi and LTE-LAA throughput gains are positive for $W^L_{min} = 2$ vs. the number of Wi-Fi STAs

Fig. 7 represents that short collisions (when RTS/CTS is used) and the fact that Wi-Fi STA transmission during the vulnerable interval does not necessarily make LTE-LAA access failed slightly enhance T_{min} and, consequently, decreases the maximum LTE-LAA gain.

It is worth mentioning that the fair resource sharing can be achieved with existing in 4G licensed spectrum slot size of $0.5ms$ if there are more than 10 Wi-Fi STAs (for instance, see Fig. 7). However, in the majority of cases, T should be significantly decreased to achieve fairness. Such a reduction will be available in 5G networks.

VI. Conclusion

In this paper, we have developed an analytical model that allows us to estimate the throughput of LTE-LAA and Wi-Fi networks when they coexist in unlicensed spectrum. Various versions of LTE-LAA implementation have been considered, in particular, with and without the reservation signal. According to the obtained results, the fair and efficient coexistence of Wi-Fi and LTE-LAA networks is almost impossible in existed 4G networks, but it will be possible in 5G systems thanks to flexible numerology of New Radio, which will reduce the period of moments when an LTE-LAA base station can start data transmission. In our future research, we are going to take into account the channel sensing nonideality, which will lead to the non-zero probability of LTE-LAA and Wi-Fi collisions when LTE-LAA implementation without reservation signal is used.

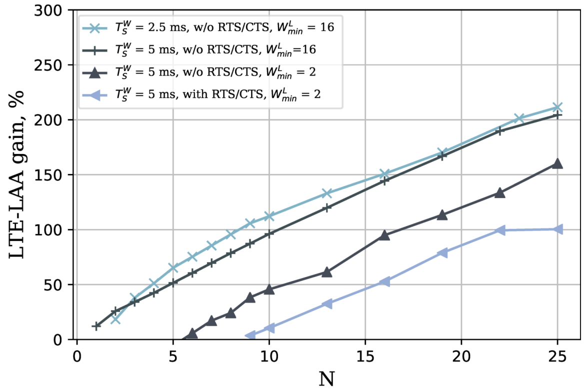

Figure 8. LTE-LAA throughput gain for $T = T_{min}$ and both Wi-Fi and LTE-LAA throughput gains are positive vs. the number of Wi-Fi STAs

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