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Latency and Reliability Analysis of Cellular Networks in Unlicensed Spectrum

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ABSTRACT In this paper, the achievable latency-reliability performance of a standalone cellular network over the 5 GHz unlicensed spectrum is analysed. Fulfilling strict latency-reliability requirements comes with significant challenges for unlicensed operation, especially due to mandatory channel access procedures. Using MulteFire as the reference system-model, an analysis of a highly realistic multi-cell network with bi-directional traffic shows that latency of 23 ms with a reliability level of 99.99% is achievable for low-loads, while latency is increased to 79 ms at high-loads. Different techniques are described to improve the system performance. First, a pre-emptive scheme to cope with continuous uplink listen before talk (LBT) failures for uplink control transmissions is proposed. It provides a latency reduction of 24% at low-loads with two transmission opportunities and 11% for high-loads with three opportunities. Secondly, the possibility of skipping LBT performance under given conditions is evaluated. This results in a lower uplink LBT failure rate which translates to a latency reduction of 8% for low-loads and up to 14% for high-loads, at 99.99% reliability. Thirdly, as an alternative to grant-based uplink, grant-free uplink is evaluated. Grant-free uplink achieves better performance than grant-based uplink at low-loads, offering 50% lower uplink latency. At high-loads, the gain of grant-free uplink decreases due to the high number of simultaneous transmissions.

INDEX TERMS Latency, reliability, unlicensed spectrum, MulteFire, listen before talk, radio resource management, system-level performance, scheduling, hybrid automatic repeat request.

I. INTRODUCTION

With the arrival of 5G New Radio (5G NR), plenty of novel use cases with diverse requirements are envisioned to be supported. The 3rd Generation Partnership Project (3GPP) has defined use cases and the corresponding requirements for enhanced mobile broadband (eMBB) in [1], mission-critical communications in [2] and massive Internet of Things (IoT) in [3]. Among the use cases defined in the mission-critical communications domain, industrial automation is foreseen as one of the most relevant use cases for private networks. Industrial automation relies on reliable and broadband connectivity to lead to the next stage in the industrial revolution, commonly known as Industry 4.0. The next industrial revolution aims to improve factory plants and production lines in four main aspects: efficiency, flexibility, usability and versatility. In [4], 3GPP describes several vertical domains use-cases including the Factories of the Future. The 5G Alliance for Connected Industries and Automation (5G ACIA) proposes industrial-specific use-cases and its corresponding requirements in [5]. Both entities agree on the need for supporting stringent requirements in latency and reliability for communications between machines, objects and people as a key enabler for the Industry 4.0.

Unlicensed spectrum is considered a valuable asset to be used by cellular technologies, especially for private network deployments. Unlicensed bands are characterised by being a global solution with low cost of operation and larger available bandwidth at below 7 GHz as compared to licensed spectrum. The 3GPP's interest in unlicensed band started with Licensed-Assisted Access (LAA). In LAA, unlicensed bands are jointly operated with an anchor cell deployed in a licensed band offering the possibility of offloading traffic to unlicensed bands [6], [7]. An independent organisation from 3GPP, the MulteFire Alliance, recently designed a system capable of operating in standalone mode in the

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unlicensed spectrum. This technology is bsaed the Long Term Evolution (LTE) specifications and it is known as MulteFire [8]. Research on unlicensed spectrum operation has continued by 3GPP during the 5G-NR development. As part of the current Release 16, 3GPP aims to design NR-Unlicensed (NR-U) as a single and global solution for unlicensed spectrum access based on NR specifications [9]. The considered unlicensed frequencies for LAA, MulteFire and NR-U are located in the 5 GHz frequency band. Currently, there are discussions about extending the frequency ranges for unlicensed operation. Regulatory entities in the United States, Europe and other parts of the world are considering the possibility of opening the 6 GHz band (5.925-7.125 GHz) [10]. Frequency bands between 57 and 71 GHz, i.e. millimetre waves, are also candidates [11], [12]. However, none of these bands are yet available for real deployments. The focus of LAA and MulteFire technologies and the first design of NR-U is to support communications with non-critical quality-of-service (QoS) requirements. Further optimisations enabling the support of demanding QoS, such as low-latency and high-reliable communications in unlicensed bands, are expected to be included in future 3GPP releases, i.e Release 17.

As compared to licensed solutions, meeting tight latency-reliability requirements in unlicensed bands brings additional non-trivial problems that need to be properly addressed. Only few available studies address the performance of latency-critical traffic with high-reliability constrains for unlicensed bands in standalone mode. Examples include [13], where the impact of listen before talk (LBT) for downlink-only traffic is analysed based on extensive system-level simulations following the MulteFire design. Similarly, the LBT influence on the uplink-only latency performance is studied in [14], including a latency-reliability comparison between grant-based and grant-free uplink schemes. As a non-standalone alternative, authors in [15] propose tight cooperation between unlicensed and licensed bands to meet the latency-reliability targets. Licensed spectrum is only used under conditions in which unlicensed spectrum represents a bottleneck for the latency-reliability performance. All these studies share a common message: channel access procedures are found to cause increased latencies as transmissions are frequently postponed due to high measured interference-levels. Therefore, supporting tight latency-reliability requirements for standalone unlicensed spectrum systems remains a challenge that calls for more research and development.

In this paper, we further study the latency-reliability performance of a private network deployment operating over the 5 GHz unlicensed band in standalone mode following the MulteFire model. We study advanced cases with time-variant bursty bi-directional traffic. A performance analysis is conducted under realistic conditions for a multi-cell and multi-user system-level. Results are obtained from a highly detailed state-of-the-art system-level simulator. We present a solid baseline performance for latency-critical and high reliable traffic for the 5 GHz unlicensed spectrum that goes beyond results available in the existing open literature. This includes analysis of how the performance varies with different parameters such as the offered traffic, as well as the impact of LBT over the total packet latency. Based on the established baseline performance, and the identified bottlenecks for achieving high reliable and low latency performance, we present multiple promising guidelines and enhancements to further optimise the performance. In particular, we show that by providing users with additional occasions for hybrid automatic request and repeat (HARQ) transmissions achieves significant latency reductions. Secondly, great latency gains at high offered load are obtained by avoiding the LBT performance during the downlink-to-uplink transitions. Finally, attractive uplink latency reductions are achieved by using grant-free as compared to scheduled transmission, especially at low to medium loads.

The paper is organised as follows: the 5 GHz regulatory aspects for unlicensed operation are described in Section II. The system model definition is included in Section III, while Section IV outlines the suggested proposals for achieving improved latency-reliability performance. Performance evaluation is provided in Section V. Finally, concluding remarks appear in Section VI.

II. REGULATORY REQUIREMENTS OVER 5 GHz BAND

The regulatory requirements for the 5 GHz unlicensed band vary depending on the region and the specific sub-band. Therefore, to be worldwide deployable, a radio access technology operating in unlicensed spectrum needs to fulfil the most stringent regulatory requirements among those standardised in various regions of the world. Besides, it needs to ensure fairness towards other co-existing radio access technologies deployed in the same frequency band. Consequently, the harmonized standard developed by the European Telecommunications Standard Institute (ETSI) is used to define the minimum requirements that 3GPP-based radio access technologies need to follow to operate in the 5 GHz band. These requirements include limitations on the transmitted power and power spectral density. There are also restrictions on the occupied channel bandwidth. The occupied channel bandwidth should be at least 80% of the nominal channel bandwidth. Additional information about ETSI regulations can be found in [16].

A. CHANNEL ACCESS PROCEDURES

In order to guarantee a fair coexistence among the different radio access technologies deployed over the 5 GHz band, each node is mandated to assess the availability of the channel before any transmission. The channel access mechanism adopted by 3GPP is based on a clear channel assessment (CCA) procedure that uses LBT in compliance with the ETSI regulations. LBT is a contention-based protocol that allows devices to use the same radio channel without pre-coordination. It is based on an energy detection (ED) threshold mechanism performed over intervals of 9 μ s, also known as CCA slots (T_s). During each CCA slot, a node detects the channel activity based on power measurement and posterior comparison with a predefined ED threshold. The medium is declared as idle during a CCA slot if, at least, the measured power is lower than the threshold for 4 μ s. Transmission is conditional on the device sensing the channel as idle for a certain number of CCA slots. Upon the idleness declaration, a device is only allowed to occupy the channel for a limited duration of time. LBT is also used by other radio access technologies deployed in the 5 GHz unlicensed band such as the IEEE 802.11 standard (Wi-Fi) which ensures fair coexistence among them [17], [18].

Two types of LBT procedures are standardized. The so-called Category 4 (Cat4) LBT implements a random backoff and a variable contention window size algorithms. Cat4 LBT consists of 1) an initial CCA (iCCA) where the channel is sensed during a defer period ($T_d = 16\ \mu\text{ s} + m_p \cdot T_s$) and, upon the success of the iCCA, 2) an extended CCA (eCCA). During the eCCA, the transmitter generates a random number from a uniform distribution defined over the contention window size. This number represents the minimum number of CCA slots the channel needs to be sensed as idle before transmitting. The transmitter can subsequently use the channel for a maximum time, also known as the maximum channel occupancy time (MCOT). The contention window size varies based on the number of unsuccessful and successful transmissions on the medium. Different values for the contention window sizes, the MCOT durations and m_p are classified into channel access priority classes (CAPC) [19]. The so-called Category 2 (Cat2) LBT, also known as single-shot LBT, defines a type of channel access procedure in which nodes can initiate a transmission after sensing the channel to be idle for a fixed duration of 25 μ s. The 25 μ s interval is split into a 16 μ s interval, which contains a CCA slot and an idle slot of 7 μ s, and an additional CCA slot. Channel is declared as free if it is sensed as idle during both CCA slots.

Cat4 LBT is used by initiating nodes to gain access to the channel. Cat2 LBT can be used by responding nodes to initiate transmissions within the previously acquired channel occupancy time (COT) by an initiating device. This is also known as COT sharing. The duration of the transmission after a successful Cat2 LBT is defined by the initiating node and it is limited by the MCOT. Furthermore, within the COT, the regulations also allow responding devices to initiate a transmission without performing LBT. The condition to skip LBT is fulfilled when the gap between the end of the transmission by the initiating device and the start of the transmission by the responding device is shorter than 16 μ s. This is known as Category 1 (Cat1) LBT. Further details about the channel access mechanism considered by 3GPP as assumed in our analysis can be found in [13], [19].

III. SYSTEM MODEL

The system model assumed throughout the paper comprises a single-operator indoor scenario with M eNBs and K UEs uniformly distributed within the building. Each node operates over the 5 GHz frequency band with a bandwidth of 20 MHz. Bi-directional traffic is generated following a homogeneous Poisson point process with an average packet arrival rate of λ_T expressed in packets/s/UE. Payloads in downlink are assumed to be generated with an average rate of λ_{DL}, while UEs generate uplink packets with an average arrival rate of λ_{UL}. Both packet arrival rates constitute the overall packet arrival rate per UE (λ_T):

$$\lambda_T = \lambda_{DL} + \lambda_{UL} \tag{1}$$

Given the model and assuming a fixed payload size of B bytes, the offered load (L) expressed in bits/s is defined as:

$$L = \lambda_T \cdot K \cdot B \cdot 8 \tag{2}$$

Dynamic time domain duplexing (TDD) is assumed. The frame configuration is dynamically updated and its downlink-uplink ratio, in terms of subframes, is adjusted based on the buffers' status at the nodes, i.e. the instantaneous traffic variation. Slot-level synchronization among the nodes is assumed whereas the frame configuration is node specific. Unless explicitly mentioned, it is always assumed that eNBs are the only node capable of starting a channel occupancy time. A single switching point between downlink and uplink subframes within the COT is supported. The transition subframe between downlink and uplink, also referred to special subframe, contains a partial ending subframe, a guard period and a short uplink subframe. The short uplink subframe, referred throughout the text as short-physical uplink control channel (sPUCCH), comprises the last 4 OFDM symbols of the special subframe and it is used for uplink control signalling transmissions, such as scheduling request or HARQ feedback [18].

A. DOWNLINK OPERATION

For downlink (DL) initiated transmissions, eNBs are considered as initiating devices. Therefore, a successful Cat4 LBT must be performed before transmitting. Due to the uncertainty about when LBT finishes, each eNB is configured to have two opportunities within a subframe to start the transmission. Specifically, OFDM symbols 0 and 7 are the candidates' starting positions. As compared to licensed operation, the additional starting position at the OFDM symbol 7 reduces the time between LBT finishes and the transmission starts, lowering the probability of channel access by a neighbour node. Upon the reception of the downlink data, the UE processes it and prepares the HARQ feedback that must be sent back to the eNB. HARQ feedback transmissions can be performed over sPUCCH or granted uplink resources.

Based on this model, the end-to-end delay of a downlink packet correctly received at first transmission can be expressed as:

$$\Psi_{DL} = \max\left[\Psi_{eNB}^{prep.}, \Psi_{Cat4}\right] + \Psi_{FA} + \Psi_{TTI} + \Psi_{UE}^{decod.}, \tag{3}$$

where Ψ_{Cat4} corresponds to the delay associated with the Cat4 LBT performed by the eNB and Ψ_{FA} accounts for time

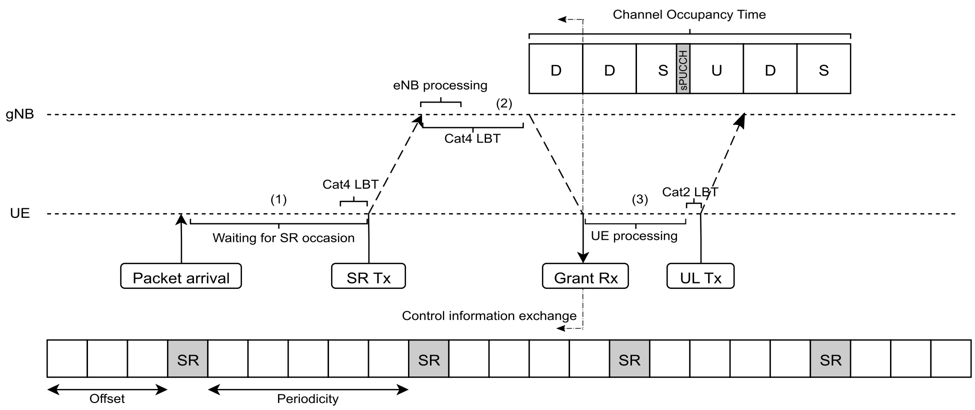

FIGURE 1. Grant-based uplink operation in unlicensed spectrum.

the eNB needs to wait until the next starting position, also known as frame alignment. Ψ_{TTI} models the transmission time interval (TTI) duration and $\Psi_{eNB}^{prep.}$ and $\Psi_{UE}^{decod.}$ corresponds to the processing time at the transmitter and receiver to prepare and decode the packet, respectively. It is assumed that eNBs prepare the data and perform Cat4 LBT in parallel.

Once the UE decodes the downlink packet, it needs to report the HARQ feedback to the eNB. The delay associated with this process equals:

$$\Psi_{HARQ} = \Psi_{HARQ}^{occ.} + \Psi_{Cat2} + \Psi_{TTI} + \Psi_{eNB}^{decod.}, \qquad (4)$$

where $\Psi_{HARQ}^{occ.}$ corresponds to the time spent by the UE while waiting for a HARQ feedback occasion, and Ψ_{Cat2} models the fixed delay associated with the Cat2 LBT, i.e. 25 μ s. The processing delay at the eNB side is represented by $\Psi_{eNB}^{decod.}$.

Assuming that q retransmissions are needed before the packet is received correctly by the UE, the overall packet delay equals to:

$$\Psi_{total} = \Psi_{DL} + q\Big[\Psi_{HARQ} + \Psi_{DL}\Big] \qquad (5)$$

Due to the dependency between LBT and the instantaneous measured interference, uncertainty over whether transmissions will be carried out is added. As a baseline, it is assumed that eNBs only provide UEs with one opportunity for transmitting the HARQ feedback, that is, the sPUCCH resources or dynamically scheduled uplink resources. In case of Cat2 LBT blocking at UE side, the control information transmission is blocked. eNB assume the absence of HARQ feedback as negative feedback which automatically triggers a retransmission. In such a case, the round trip time (RTT), i.e. the time from the packet transmission until the acknowledgement is received at the transmitter side, is defined as follows:

$$\Psi_{RTT} = (r+1)\Big[\Psi_{DL} + \Psi_{HARQ}\Big], \qquad (6)$$

where r accounts for the number of missing HARQ opportunities due to Cat2 LBT blocking. Note that, in these equations, the contribution of the queuing delay is neglected and equal processing times for new data transmissions and retransmissions are assumed.

B. UPLINK OPERATION: GRANT-BASED UPLINK

Uplink (UL) transmissions can be performed using grant-based (GB) scheduling. By means of GB uplink, a UE is capable of transmitting data over a specific set of resources granted by its serving eNB. Operation according to GB uplink is depicted in Figure 1. Before any uplink data transmission takes place, UEs and eNBs need to go through a control information exchange to agree on which time-frequency resources will be used. This handshake process is as follows:

1) First, the UE transmits a scheduling request (SR) message in which it requests resources to be used for a new uplink data transmission. SR transmissions are performed over specific physical uplink control channel (PUCCH) resources, i.e. SR-PUCCH, which are configured by higher layers with certain periodicity and offset. The specific resources are used, provided that they do not collide with physical downlink shared channel (PDSCH) or physical uplink shared channel (PUSCH) transmissions. In such cases, the UE attempts the SR transmission in the next SR occasion.
2) Upon SR message reception and after a eNB-specific processing time, the eNB sends a grant in which it dynamically schedules the UE in uplink.
3) The grant is decoded by the UE and the PUSCH preparation starts. The time between the grant is received and the UE is capable of transmitting the PUSCH is known as scheduling delay. Assuming LTE processing capabilities, the scheduling delay is 4 ms.

As shown in Figure 1, applying GB uplink for unlicensed operation implies the performance of multiple channel access procedures. The type of LBT used depends on the current COT conditions. For SR transmissions, UEs can either use Cat4 LBT with high CAPC or Cat2 LBT depending on the COT sharing conditions. For uplink grant transmissions, the eNB is considered as an initiating node and, therefore, it needs to perform a Cat4 LBT. The eNB grants permission

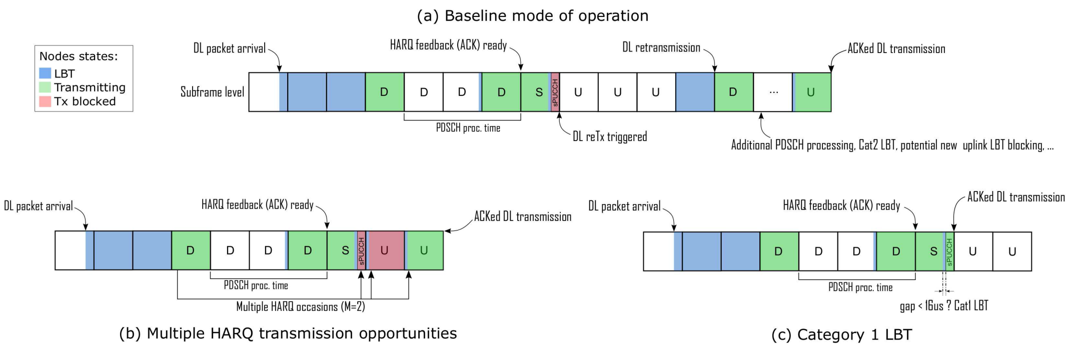

FIGURE 2. **Baseline mode of operation in (a) and latency reduction proposals. Multiple HARQ feedback opportunities in (b) and Cat1 LBT in (c).**

to the UE to use COT sharing, and after the corresponding UE processing time, the PUSCH transmission occurs upon a successful Cat2 LBT. Furthermore, to fulfil the bandwidth regulations defined in Section II, a new waveform is designed as alternative to single-carrier frequency domain multiplexing access (SC-FDMA) used for GB uplink in licensed bands. The adopted solution, known as block interleaved frequency division multiple access (B-IFDMA) [20], spans the frequency domain allocation of each UE over the available transmission bandwidth. Each UE is assigned with one interlace as minimum frequency domain allocation. An interlace is a set of M frequency equidistant physical resource blocks (PRBs).

Regarding the delays involved in GB uplink, the time spent in the control information exchange can be expressed as:

$$\Psi_{SR} = \max\left[\Psi_{UE}^{prep.}, \Psi_{Cat4}, \Psi_{SR}^{occ.}\right] + \Psi_{TTI} + \Psi_{eNB}^{decod.} + \max\left[\Psi_{eNB}^{prep.}, \Psi_{Cat4}\right] + \Psi_{FA} + \Psi_{TTI}, \quad (7)$$

where $\Psi_{SR}^{occ.}$ defines the time spent while waiting for SR-PUCCH resources. In (7), it is assumed that UE is not in COT sharing conditions and, therefore, Cat4 LBT is performed prior to the SR transmission. Given (7), the end-to-end delay for an uplink packet correctly received at first transmission equals:

$$\Psi_{UL} = \Psi_{SR} + \Psi_{UE}^{prep.} + \Psi_{Cat2} + \Psi_{TTI} + \Psi_{eNB}^{decod.}, \quad (8)$$

where $\Psi_{UE}^{prep.}$ represents the preparation time of the uplink transmission after the grant reception at the UE side, i.e. the scheduling delay and $\Psi_{eNB}^{decod.}$ models the eNB processing time of the uplink packet at the eNB side. In this equation, successful Cat2 LBT has been assumed. Note that throughout these equations the contribution of the queuing delay is neglected.

IV. LATENCY REDUCTION PROPOSALS

Three different latency reduction solutions are presented in this section. The first two methods aim to mitigate the impact of Cat2 LBT failure when transmitting HARQ feedback for previously received downlink transmissions. The latter proposal presents a technique to reduce the uplink delay by means of alleviating the two main problems related to GB uplink: the multiple channel accesses needed in the control information exchange and the intrinsic scheduling delay.

A. MULTIPLE HARQ FEEDBACK OPPORTUNITIES

As introduced in Section III and shown in Figure 2(a), a failure in the Cat2 LBT prior to a HARQ feedback transmission triggers additional retransmissions. Additional downlink transmissions might be unnecessary as the UE could have decoded correctly the packet, i.e ACK message is ready to be transmitted, but it was not able to access the channel within the specific resources due to LBT blocking. Unnecessary retransmissions will cause: 1) additional interference in the system which may delay neighbour's transmissions since they could be blocked by LBT, 2) a reduction in the system resource efficiency as no additional information is transmitted in subsequent transmissions and 3) the performance of multiple successful Cat4 LBT. Moreover, it increases the queuing delay for new incoming packets, since they will not be served until previous transmissions are correctly acknowledged. As expressed in (6), the RTT delay is highly impacted by the number of missed HARQ feedback opportunities. Additionally, a discontinuous transmission (DTX) detection by the eNB can potentially increase the Cat4 LBT contention window size which, in turn, implies larger channel access delays [19].

To cope with this problem, a solution in which UEs are provided with multiple and consecutive opportunities for transmitting HARQ feedback is proposed. Thereby, each eNB is in charge of signalling, via the downlink control channel, the resources over which UEs can transmit the HARQ feedback. As depicted in Figure 2(b), a UE using this scheme will be allowed to transmit ACK/NACK feedback in $M + 1$ occasions during the following uplink burst. Through this procedure, the probability of being blocked by Cat2 LBT failure is reduced and, therefore, the number of unnecessary retransmissions, i.e. the component r in (6), is also decreased. By comparing Figures 2(a) and 2(b), a shorter RTT is achieved with the proposed solution. It is worth noticing that this scheme offers a trade-off between Cat2 LBT reduction and resource efficiency as pre-emptive resources

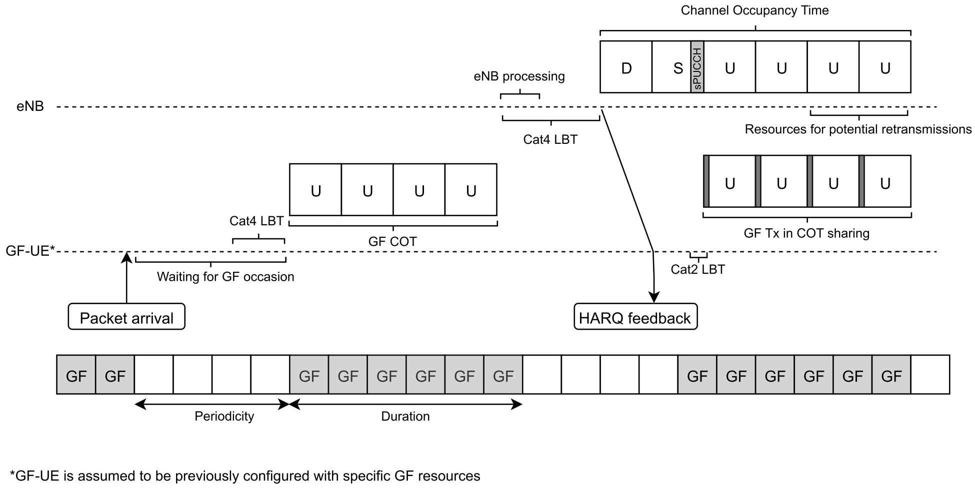

FIGURE 3. Grant-free uplink operation in unlicensed spectrum.

are reserved for potential HARQ feedback transmissions that may not be used if Cat2 LBT succeeds earlier.

B. CATEGORY 1 LBT

This approach aims to reduce the Cat2 LBT blocking probability, and consequently the potential downlink retransmissions, by avoiding the LBT performance. As defined in Section II-A and depicted in Figure 2(c), a UE can start an uplink transmission without performing Cat2 LBT if the gap between the last downlink transmission and the start of uplink transmission is shorter than 16 μs. Given the system model assumptions, the only transmission in which UEs can leverage from this advantage is the HARQ feedback transmission performed over sPUCCH resources. If an eNB is capable of transmitting during the partial ending downlink of the special subframe, the UEs which have HARQ feedback from previous downlink receptions ready for transmission can access the channel without performing LBT.

C. GRANT-FREE UPLINK

GB presents two main drawbacks from a delay perspective. Firstly, it needs to go through a lengthy control information exchange prior to the actual uplink data transmission, as shown in Figure 1 and (7). In addition to this, uplink transmissions are constrained by a fixed delay upon the reception of the grant, i.e. the scheduling delay. Moreover, employing GB uplink in the unlicensed spectrum could be seen as less appropriate, due to the performance of multiple LBTs which adds uncertainty over the transmission performance. For instance, a UE may fail at accessing the channel due to a Cat2 LBT blocking prior to the PUSCH transmission. This will lead to a decrease in resource efficiency as the granted resources will not be used. In such a case, the eNB will reschedule the UE for a second attempt transmission. This situation will lead to higher delays for uplink packets and it also may block the transmission of neighbour cells since the channel needs to be occupied for longer periods.

In order to mitigate the disadvantages of GB uplink, grant-free (GF) uplink is proposed. A description of the GF mode of operation is shown in Figure 3. As compared with GB uplink, GF transmissions allow UEs to perform uplink transmissions avoiding the handshake process used in GB uplink. To achieve that, grant-free UEs (GF-UEs) are configured in a way that uplink transmissions occur over predefined and, potentially, shared resources among multiple UEs. In the time domain, the specific resources are given by the serving eNB based on periodicity and a duration. For frequency domain, GF-UEs are assumed to be configured by the serving eNB with a combination of interlaces, also known as frequency domain pool (FD-PL).

Analytically, the configuration of the GF resources substitutes the delay-prone SR procedure defined in (7) by:

$$\Psi_{GF}^{config} = \max\left[\Psi_{eNB}^{prep.} + \Psi_{Cat4}\right] + \Psi_{FA} + \Psi_{TTI} + \Psi_{UE}^{decod.} \quad (9)$$

where $\Psi_{eNB}^{prep.}$ and $\Psi_{UE}^{decod.}$ model the delay for preparing and decoding the GF configuration at eNB and UE, respectively. Once the UE is configured with GF resources, this process can be avoided for subsequent uplink transmissions as the configuration remains valid for certain interval of time. This differs from GB uplink in which each uplink transmission needs to go through the SR procedure.

Given the prior knowledge over the grant-free resources, GF-UEs can prepare and start their uplink transmissions without requesting a specific grant. This speeds up the uplink transmissions as the scheduling delay, i.e. $\Psi_{UE}^{prep.}$ in (8), is neglected. Moreover, the number of channel access involved in the process is reduced by a factor of 3 as it can be noted by comparing Figures 1 and 3. This reduction in the number of required LBTs will lower the transmission delays. GF-UEs support the possibility of starting a grant-free transmission without sharing the COT with the serving eNB. In this case, Cat4 LBT must be performed as the GF-UE is the initiating device. In the case of COT sharing between the eNB and GF-UEs, Cat2 LBT is supported.

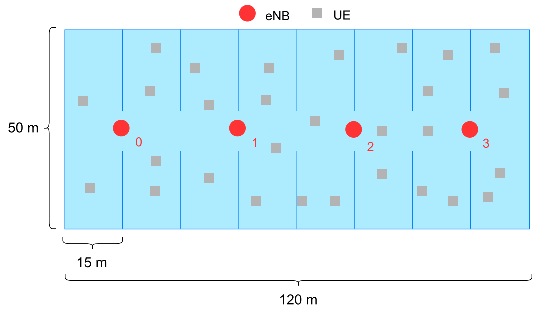

FIGURE 4. Scenario layout compliant with 3GPP guidelines for LAA performance evaluation.

The end-to-end delay of an uplink packet correctly received at first transmission when using GF approach can be expressed as:

$$\Psi_{GF} = \max\left[\Psi_{UE}^{prep.}, \Psi_{Cat4}, \Psi_{GF}^{occ.}\right] + \Psi_{TTI} + \Psi_{eNB}^{decod.}, \quad (10)$$

where $\Psi_{GF}^{occ.}$ models the time spent while waiting for GF resources. Here, the contribution of Ψ_{GF}^{config} is neglected as it is assumed that the GF-UEs were previously configured. The reduction in the number of channel access between GB and GF is observed by comparing (7)-(8) and (10).

The main disadvantage of GF-uplink is the lack of coordination inherited from a non-grant based approach. Therefore, collisions between several UEs, i.e. multiple transmissions using the same time-frequency resources, may occur. This will potentially have an impact on the receiver side as it may not always be able to decode correctly the uplink information coming from multiple sources. In order to cope with failures in the decoding, two mechanisms are proposed. The first one relies on HARQ protocol to request retransmissions to those UEs that the eNB was not able to decode. Since multiple collisions between GF-UEs are the main source of failure at GF-transmissions decoding, eNBs will send specific grants providing dedicated resources to UEs. Additionally, different starting transmission points can be defined at the transmitter side to reduce the collisions between grant-based UEs and GF-UEs. This is achieved by introducing an eNB-configured offset. By applying that, GF transmissions can be deferred for a duration up to 1 OFDM symbol, assuming an offset duration of 34 μ s in our system model. By using this approach, and considering that GB transmissions start at the slot boundary, a higher priority is given to scheduled transmissions as potential LBT blocking by GF-transmissions is avoided. This mode of operation reduces the multiplexing of GB and GF transmissions within the same TTI.

V. PERFORMANCE EVALUATION

A. SIMULATION METHODOLOGY

Our indoor scenario follows the 3GPP guidelines for LAA simulation studies [6], which consists of a single-floor indoor office with an area of 120 × 50 m^2 and several walls separated by 15 m as depicted in Figure 4. In order to emulate a private deployment, single operator conditions are assumed. A total of 4 eNBs are deployed over the scenario with an equal separation of 30 m. 50 UEs are randomly placed in the scenario. Each UE selects its serving eNB based on the strongest reference signal received power (RSRP) criteria. Performance evaluations are carried out using different offered traffic loads. A fixed packet size is assumed and the packet arrival rate (λ_T) is modified. The payload size is set to 50 bytes and λ_T takes values from the set: {25, 50 125, 250} (packets/s/UE), which corresponds to the offered loads of: {0.5, 1, 2.5, 5} (Mbit/s), respectively. Bidirectional traffic is assumed, 80% of the overall traffic is generated at eNBs side ($\lambda_{DL} = 0.8\lambda_T$), whereas the remaining 20% is generated at the UEs ($\lambda_{UL} = 0.2\lambda_T$).

For GB uplink operation, it is assumed that SR opportunities occur every subframe, i.e. 1 ms periodicity. It also assumed that the eNB delays for decoding the SR message and generating the grant are neglected. Grant transmissions are only performed over downlink subframes upon the acquisition of the channel. The PUSCH preparation time equals to 4 TTIs, i.e. 4 ms. Frequency domain scheduling is performed in an interlace basis. Based on the defined bandwidth of 20 MHz and the 15 kHz sub-carrier spacing, each interlace is formed by 10 PRBs which results in a total of 10 available interlaces per TTI.

For GF uplink operation, a GF resources periodicity of 1 ms is assumed. Frequency resources are configured in advance by the serving eNB, where each UE is signalled with a frequency domain pool (FD) consisting of 5 interlaces. Frequency domain pool-1 (FD-1) includes the interlaces {0,2,4,6,8} whereas FD-2 consists of the interlaces {1,3,5,7,9}. Additional simulation assumptions can be found in Table 1.

The simulator models with high-level of details the majority of the PHY and MAC functionalities and procedures in line with 3GPP guidelines. It dynamically schedules users in time and frequency domains, uses HARQ in case of decoding failures or performs link adaptation based of channel quality indicator (CQI) reports to fulfil the target block error rate (BLER). Moreover, all the regulatory channel access aspects for operating on the 5 GHz unlicensed band are carefully modelled. The simulator operates on symbol-level and subcarrier resolution. For each transmission, the SINR at the receiver is calculated for each subcarrier symbol, assuming a linear minimum mean square error with interference rejection combining (LMMSE-IRC) receiver [22]. Inspired by the model in [23], [24], the SINR values are mapped to the mutual information domain, taking the applied modulation scheme into account. The mean mutual information per coded bit (MMIB) is calculated as the arithmetic mean of the values for the subcarrier symbols of the transmission [24]. Given the MMIB and the used modulation and coding rate of the transmission, the error probability is determined from look-up tables that are obtained from extensive link level simulations. Furthermore, it includes proven stochastic models for radio propagation, calibrated against alike models used in 3GPP system level simulations. In order to get statistically stable

TABLE 1. Simulation assumptions.

Feature	Assumption
Layout	Indoor single floor 3GPP TR 36.889, Annex A.1.1 [6]
Channel model	ITU Indoor Hotspot
Duplexing mode	Dynamic TDD
Bandwidth	20 MHz, 15 kHz sub-carrier spacing
TTI	14 OFDM symbols
Scheduling metric	Proportional fair Max. scheduled UEs per TTI: 10
Scheduling type	DL: physical resource block based UL: interlace based
HARQ	Asynchronous HARQ, incremental redundancy 6 retransmissions at maximum Processing delay at eNB: 2 TTIs Processing delay at UE: 4 TTIs
Link adaptation	Outer link loop adaptation: enabled [21] Block error rate target: 1%
Receiver type	LMMSE-IRC [22]
MIMO	2x2 configuration DL: Rank-2 SU-MIMO UL: Rank-1 SU-MIMO, receiver diversity
Traffic model	B = 50 bytes $\lambda_T = \{25, 50, 125, 250\}$ (packets/s/node)
Channel Access (Initiating node: eNB)	Cat4 LBT with CAPC 3 MCOT: 8 ms Contention window sizes = $\{15, 31, 63\}$
Channel Access (Initiating node: GF-UE)	Cat4 LBT with CAPC 1 MCOT: 4 ms Contention window sizes = $\{7, 15\}$
LBT ED threshold	-72 dBm

and reliable results, multiple realizations of the scenario are simulated. For each realization, the UE locations are selected independently and sufficient samples are collected. Results from each realization are combined afterwards.

B. SIMULATION RESULTS

In this section, we highlight the improvement in latency-reliability that the aforementioned proposals can provide to an LTE-like standalone system in unlicensed spectrum. Proposals performance are compared against MulteFire baseline approach. MulteFire baseline assumes the usage of single HARQ feedback opportunity, Cat2 LBT in any conditions and grant-based uplink. In order to improve the readability at very high percentile, such as 99.99th percentile, the main key performance indicators (KPI) are represented using empirical complementary commutative distribution functions (CCDF).

1) DOWNLINK

Figure 5 shows the CCDF of the downlink delay per packet when using multiple HARQ feedback opportunities. Three different cases are compared. For the baseline case, i.e. with M = 0, it is assumed that a Cat2 LBT failure in sPUCCH or granted resources for HARQ transmissions it is translated

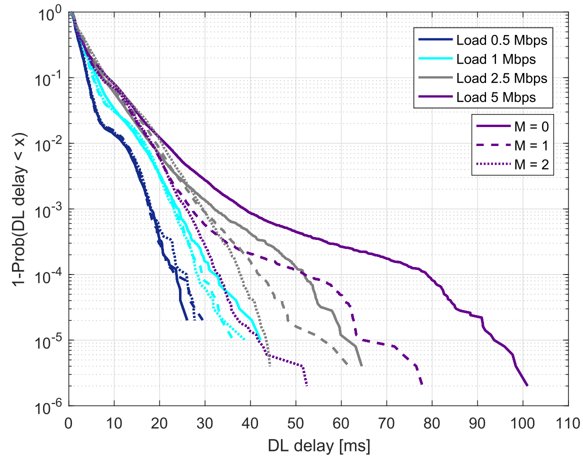

FIGURE 5. CCDF of the delay per downlink packet when multiple HARQ opportunities scheme is used. Solid lines represent baseline assumptions, i.e. M = 0, dashed lines and dotted lines refer to M = 1 and M = 2, respectively.

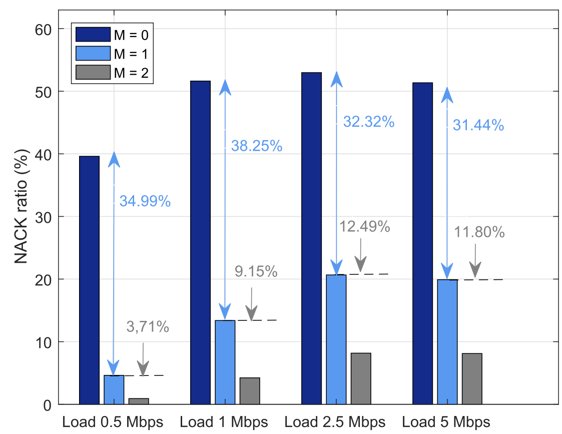

FIGURE 6. Negative acknowledgement ratio for M = 0, i.e. baseline assumptions, M = 1 and M = 2 for 4 different system loads.

into a downlink retransmission. M = 1 and M = 2 refer to the cases where the serving eNB provides 1 or 2 additional opportunities to transmit the ACK/NACK feedback, respectively. It is noted that an improvement is achieved when using this scheme for loads from 1 Mbps to 5 Mbps. At 0.5 Mbps load, the generated traffic is low enough that the downlink delay performance is not impacted by the additional retransmissions. This is shown in the CCDF, as M = 1 and M = 2 do not provide better performance as compared to baseline assumptions. In fact, the scheme is performing slightly worse from a downlink delay point of view. This is due to the fact that when providing additional feedback opportunities, UL bursts extend their duration during the next TTIs which, in turns, delays the starting of the channel access procedure for the next COT. For M = 2, it provides reasonable improvement for 2.5 Mbps and 5 Mbps, i.e. the high load cases, whereas for 1 Mbps the latency reduction is minimum as compared to M = 1.

In Figure 6, the NACK ratio, that is the number of PDUs considered as NACK due to Cat2 LBT divided by the total number of downlink PDUs received by each UE, is plotted.

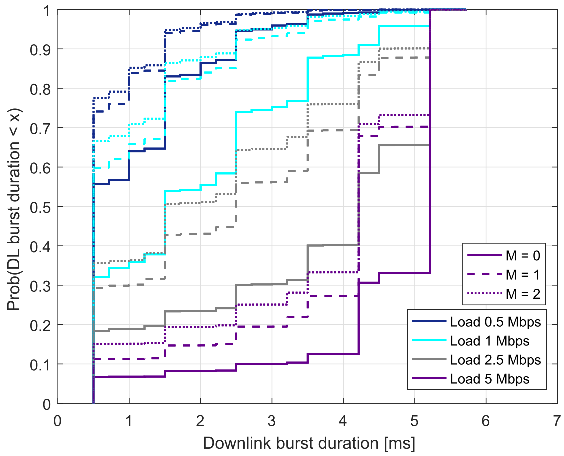

FIGURE 7. CDF of the duration of the downlink burst for the different loads. Solid lines represent baseline assumptions, i.e. M = 0, dashed lines and dotted lines refer to M = 1 and M = 2, respectively.

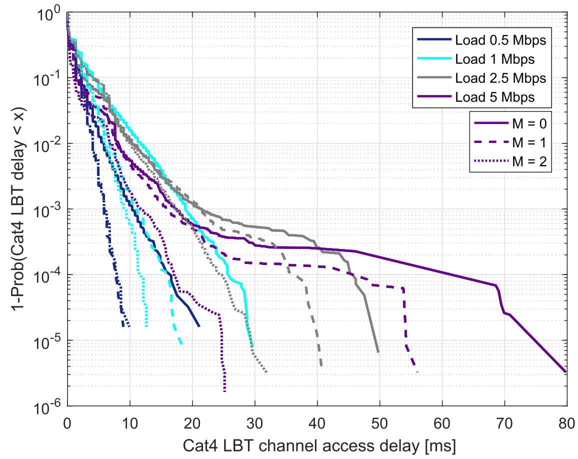

FIGURE 8. CCDF of the time spent performing Cat4 LBT by the eNBs. Solid lines represent baseline assumptions, i.e. M = 0, dashed lines and dotted lines refer to M = 1 and M = 2, respectively.

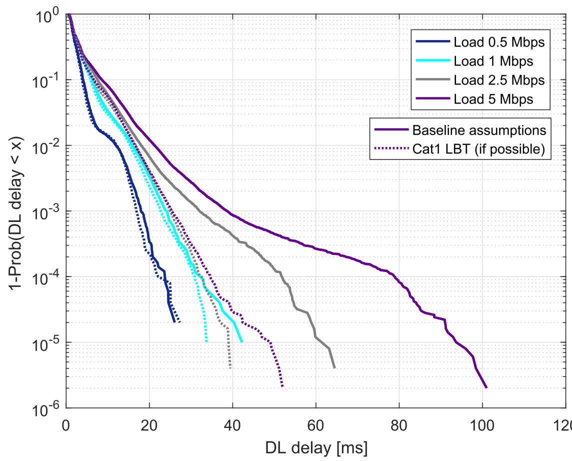

FIGURE 9. CCDF of the delay per packet in downlink. Solid lines represent baseline assumptions while dotted lines show the delay when Cat1 LBT is considered.

It is noted that, for all the considered loads, a reduction in NACK ratio is achieved when using multiple occasions for signalling the HARQ feedback. Specifically, providing an additional HARQ transmission opportunity (M = 1) highly reduces the NACK ratio at low-load cases, i.e. 0.5 Mbps and 1 Mbps, whereas at high-load cases, i.e. 2.5 Mbps and 5 Mbps, the improvement is limited. This is due to the fact that, at high-load cases, the interference which is blocking UEs at the first ACK/NACK transmission attempt is likely to continue in next subframes as compared to the low-load cases. Therefore, additional opportunities are required in these cases. M = 2 is needed to reach NACK ratios bellow 10% for the high-load cases.

The fact that less retransmissions are triggered by the serving eNBs has an immediate effect in the duration of the downlink burst during the COT and, in turn, in the interference level. In Figure 7, a comparison between the duration of the downlink burst for the three different cases is shown. It is noted that the scheme brings a reduction in the downlink burst duration for all the considered loads. The reduction in the interference level highly impacts both neighbour eNBs and UEs channel access procedures. In Figure 8, a comparison among the eNBs channel access delays is presented. A reduction in the time spent performing the Cat4 LBT is acquired in all the considered loads. Moreover, it reduces the RTT delay, as well as, the queuing delay as new packet transmissions can be served in shorter time.

Figure 9 provides a latency-reliability comparison between baseline simulations, i.e. UEs are always mandated to perform Cat2 LBT prior to any transmissions, and simulations in which UEs are configured to skip the Cat2 LBT if the gap with the last downlink transmission and the next uplink transmission is lower than 16 μ s. It can be noted that the enhancement is highly impacting the high-load cases, whereas low-load cases do not experience such benefit. This is because at low-load regime, the serving eNB rarely can extend its transmission during the partial ending subframe of the special subframe and, thus, the gap is higher than 16 μ s. On the other hand, in the high-load cases, it is more likely that eNBs have enough downlink data to keep transmitting until reaching the DL-UL gap in the special subframe. As shown in Figure 10, the probability of being blocked while performing Cat2 LBT is significantly reduced when implementing the proposal reaching the lowest probability at 18% when having 5 Mbps offered load. Looking at the achieved blocking probabilities, it is noted that it is highly likely that a UE is blocked on the sPUCCH resources at any of the considered loads. The main contributor to this is the well-known hidden node problem. This happens when an eNB performs a successful Cat4 LBT and allows COT sharing with its serving UEs. Although the eNB initially sensed the channel as clear, the UEs are exposed to interference coming from neighbour nodes that are out of the range of the eNB. This undiscovered interference by the eNB is preventing UEs to use the channel for potential transmissions. The fact that the blocking probability is lower for the high-load cases compared to the

TABLE 2. Summary results: Delay reduction in percentage compared with baseline assumptions.

Reliability	Load	Multiple HARQ opportunities	Cat1 LBT
99.9^{th} percentile	1 Mbps	DL: 3.5%; UL: 22.1%; (M = 1)	DL: 6.2%; UL: 10.6%
	5 Mbps	DL: 28.5%; UL: 3.1%; (M = 2)	DL: 34.3%; UL: 10.2%
99.99^{th} percentile	1 Mbps	DL: 8.8%; UL: 10.8%; (M = 1)	DL: 4.2%; UL: 11.4%
	5 Mbps	DL: 55.2%; UL: 18.3%; (M = 2)	DL: 55.2%; UL: 24.8%

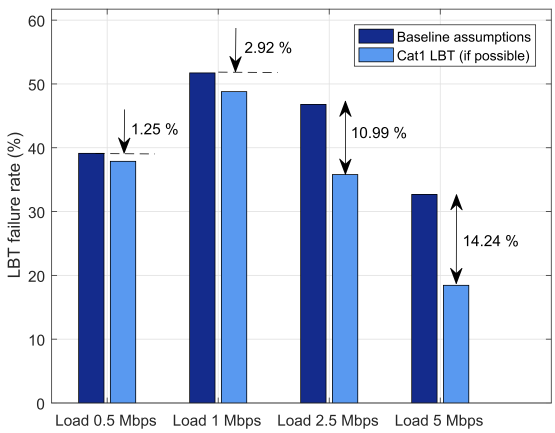

FIGURE 10. Probability of being blocked while accessing the channel over sPUCCH resources by a Cat2 LBT.

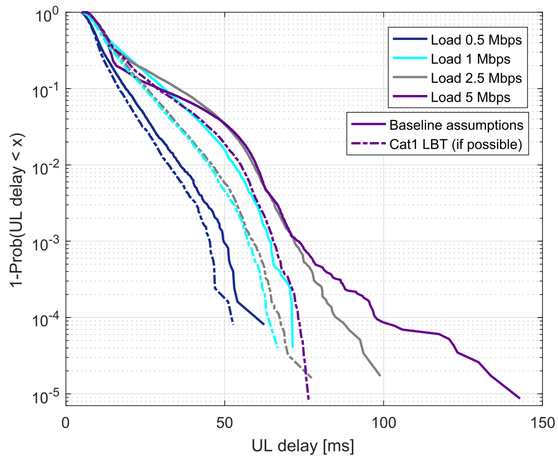

FIGURE 11. CCDF of the delay per packet in uplink. Solid lines represent baseline assumptions while dotted lines show the delay when Cat1 LBT is considered.

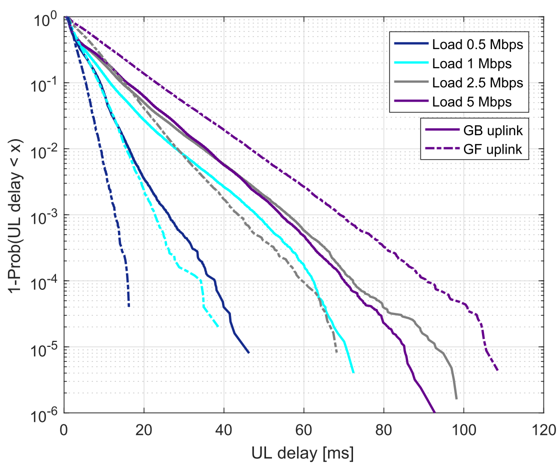

FIGURE 12. CCDF of the delay per packet in uplink. Solid lines represent grant-based uplink performance while dotted lines show grant-free uplink.

low-load cases is due to an unpredictable coordination in the frame selection is achieved. By aligning the uplink transmissions, the LBT instances are also aligned, which makes the UEs sense the channel as free more frequently.

Even though both previously mentioned solutions are directly aiming at reducing the impact of Cat2 LBT when HARQ feedback is transmitted, they also indirectly impact the latency for uplink packets. This is due to the fact that, if the number of downlink retransmissions is reduced, uplink packets can be served faster in a TDD system. Moreover, since interference in the system is also reduced, the LBT blocking probability is lowered. Figure 11 shows the reduction in the uplink delay per packet when using Cat1 LBT. Reduction of the uplink latency is achieved for every offered loads. For further description of the delay improvement provided by the aforementioned techniques, see Table 2.

2) UPLINK

A reliability-latency performance comparison between grant-based uplink and grant-free uplink is provided in Figure 12. It is observed that for 0.5 Mbps and 1 Mbps cases, the GF scheme outperforms the GB uplink. Specifically a latency reduction of 58% and 44% is achieved at 99.99% reliability for 0.5 Mbps and 1 Mbps, respectively. Benefits are obtained due to the skipping of the SR procedure and the scheduling delay. Moreover, these offered loads maintain the number of collisions at a considerable low rate, i.e. the likelihood that 2 UEs transmit over the same shared resources is low. However, when the load is increased up to a certain point the eNB is not capable to decode the multiple transmissions due to the high number of collisions. This is observed when the load is increased up to 5 Mbps. At this offered load, grant-based uplink outperforms grant-free uplink, obtaining 23% lower latency performance at 99.99% reliability.

VI. CONCLUSION

A detailed system-level latency-reliability analysis of standalone operation in unlicensed spectrum has been presented for a multi-cell/multi-user scenario with dynamic bi-directional traffic. In line with our initial hypothesis, it is found that the latency-reliability performance is severely limited by the channel access procedures. Specifically, it accounts for an average over the considered loads of 78% and 44% of the total one-way packet latency budget for downlink and uplink respectively at 99.99 reliability. Several latency-reduction solutions have been presented and evaluated. Using multiple HARQ occasions have been shown to achieve a significant reduction in the NACK ratio. On average for all the considered offered traffic load, a 34% reduction in the NACK ratio is achieved when providing an additional ACK/NACK transmission opportunity. This translates to latency reduction of 26% of the downlink delay at 99.99 reliability for highly loaded cases. An additional NACK ratio reduction of 9% is achieved when $M = 2$. This is especially noticeable at high-offered traffic loads. Providing multiple HARQ opportunities allows the system to serve new transmissions faster and, thereby, reducing the queuing delay. Additionally, it is shown that Cat1 LBT provides substantial advantages as compared to baseline simulations. Especially at high-loads, it achieves a 14% LBT failure probability reduction as compared to baseline at 5 Mbps load. It has been verified that this reduction impacts the delay per packet in both downlink and uplink transmissions. For downlink delay, reductions of 5% and 46% have been achieved at 99.99 reliability for low-loads and high-loads, respectively. The uplink delay impact shows a reduction of 13% and 17% at the same reliability level for low and high-loads, respectively. As an uplink specific enhancement, the grant-free scheme was studied and compared with grant-based operation for different loads. It was shown that the system load plays an important role for the performance benefits of GF. We have shown that a latency of reduction of 52% has been achieved with a reliability level of 99.99 for low-loads. At the maximum considered offered load, the latency achieved by GF exceeds the latency provided by GB by 23%.

There is now ongoing research to further improved the latency and reliability performance for standalone unlicensed band operation by the introduction of NR-U. Latency-reliability analysis of NR-U and related enhancements are therefore currently an active research area. Further technology enhancements for supporting stringent latency-reliability requirements are expected as part of future 3GPP releases.

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Views expressed in this contribution are those of the authors and do not necessarily represent the project.

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