Channel Access Enhancements in unlicensed spectrum for NR URLLC transmissions

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***Abstract*—Ultra-reliable low-latency communication (URLLC) is one of the main services in 5G New Radio (NR) to serve the applications with the strict requirements of latency and reliability. Increase of mobile traffic and bandwidth requirements for new applications have resulted in a shortage of licensed spectrum so that even URLLC services are deemed to be running over the unlicensed spectrum. This may require a significant re-design of channel access, transmission and reception procedures over the unlicensed spectrum and is currently being investigated in The 3rd Generation Partnership Project (3GPP) Release 17.**

This paper focuses on the channel access mechanism for URLLC services over the unlicensed spectrum. It provides an analytical analysis of current channel access procedures, listen before talk (LBT). LBT states in random duration channel access are modeled through Markov chains which help characterize the closed form expressions for average channel access time. These expressions are evaluated using the parameters from currently standardized channel access priority classes. The evaluation shows the total inability of several current channel access classes to support URLLC services over the unlicensed spectrum even under low load conditions.

The insights gained from this analysis lead the proposal of new channel access priority classes where new special classes are introduced for URLLC services. The results are provided demonstrating the improved performance of URLLC services in the unlicensed spectrum with the proposed changes in the channel access procedures.

***Index Terms*—5G, URLLC, unlicensed spectrum, Type 1 channel access procedures, channel access priority class**

I. INTRODUCTION

A. Ultra-reliable low-latency communication (URLLC)

The advent of the applications including industrial process automation, autonomous vehicles, factory automation with strict requirements of latency and reliability makes the 3rd Generation Partnership Project (3GPP) define URLLC as one of the main service in 5G since Release 15.

The URLLC requirements are defined in [1]: "A general URLLC reliability requirement for one transmission of a packet is 10^{-5} for 32 bytes with a user plane latency of 1 ms". Higher requirements are aimed in the URLLC designing objectives of Release 16: "Higher reliability (up to 10^{-6}), higher availability, short latency in the order of 0.5 to 1 ms, depending on the use cases (factory automation, transport industry and electrical power distribution)" [2].

B. URLLC physical layer design in Release 15 and Release 16

Several techniques in physical layer design have been standardized by 3GPP in Release 15 and Release 16 to make the system satisfy URLLC requirements.

Subcarrier spacing (SCS) is flexible with the values of 15 kHz, 30 kHz, 60 kHz, 120 kHz and 240 kHz instead of a single value of 15 kHz in Long Term Evolution (LTE) so that length of Orthogonal frequency-division multiplexing (OFDM) symbol decreases and the system suits large bandwidth on high frequency carriers [3].

Physical downlink shared channel (PDSCH)/physical uplink shared channel (PUSCH) mapping Type B is supported so a transport block (TB) is transmitted in the transmission time interval (TTI) of 2, 4 or 7 symbols [3]. Alignment time decreases because the TB is not buffered until the beginning of the next slot as in PDSCH/PUSCH mapping Type A.

The user equipment (UE) can be configured by the base station (gNB) to transmit uplink (UL) data in configured-grant (CG) resources without sending scheduling request (SR) and receiving UL grant to reduce latency [4]. One UE can be configured to the CG resources in different configurations. Furthermore, the UE can transmit several repetitions in the consecutive slots in PUSCH repetition Type A or in the consecutive transmission occasions in PUSCH repetition Type B without hybrid automatic repeat request (HARQ) feedback to increase reliability [4].

C. URLLC in unlicensed spectrum

All URLLC standardized techniques in Release 15 and Release 16 are for transmission in licensed spectrum. However, an increase of traffic demand in licensed spectrum causes a shortage of bandwidth for the transmission. For this reason, unlicensed spectrum attracts the attention due to its low cost, high flexibility and availability of bandwidth. Because of these advantages, URLLC in unlicensed spectrum has become one of work items for Release 17.

URLLC in unlicensed spectrum poses a challenge of latency. The transmitter must do Listen Before Talk (LBT) procedure to acquire the channel before a transmission which harms latency. There are two types of LBT procedure. Type 1 channel access procedures are used to acquire a channel in a new channel occupancy time (COT) while Type 2 channel access procedures are used to allow the UE/gNB to share the COT previously acquired by the gNB/UE. LBT procedures cause additional delay in the transmission compared to transmission in licensed spectrum due to the unpredictability of transmission opportunity. Therefore, the impact and improvements of LBT procedures must be studied to guarantee URLLC latency requirement.

D. Prior art

[6] discusses URLLC in unlicensed spectrum with the potential enhancements in physical and Media Access Control (MAC) layer to satisfy the URLLC requirements without going in detail the impact and enhancement of LBT procedures.

Several different types of LBT procedure are analyzed in [7], [8]. These types of LBT procedure do not contain defer duration after a busy sensing slot as Type 1 channel access procedures analyzed in this paper.

The expressions of LBT latency in [9], [10] neglect the contribution of the additional defer duration after a busy sensing slot. LBT latency based on these expressions has less impact on transmission latency so the channel and LBT conditions required to satisfy URLLC requirements cannot be calculated to be close to reality.

[11] does not provide in detail the transmission probability of a transmitter and a closed-form expression of latency of Type 1 channel access procedure.

This paper focuses on the impact and the enhancements of Type 1 channel access procedures in unlicensed spectrum to ensure URLLC latency requirement. Section II presents a system model of Type 1 channel access procedures by introducing a Markov chain and the parameters in the calculation. The probability of each state in Markov chain of Type 1 channel access procedures as well as the transmission probability of a transmitter are also calculated in Section II. After that, a closed-form expression of latency due to Type 1 channel access procedures is derived. This expression is used in calculating latency of a transmission in unlicensed spectrum. Section III shows the latency of Type 1 channel access procedures, total DL and UL transmission time in unlicensed spectrum. From the results, the proposals of dedicating the specific channel access priority class to URLLC and using new tables of channel access priority class to meet URLLC requirements are made. Section IV concludes this paper.

II. Analysis of Type 1 channel access procedures in unlicensed spectrum

A. System model

TABLE I
CHANNEL ACCESS PRIORITY CLASS FOR DL

Channel access priority class (p)	m_p	$T_{mcot,p}$	**Allowed CW_p sizes**
1	1	2ms	{3, 7}
2	1	3ms	{7, 15}
3	3	8 or 10ms	{15, 31, 63}
4	7	8 or 10ms	{15, 31, 63, 127, 255, 511, 1023}

TABLE II
CHANNEL ACCESS PRIORITY CLASS FOR UL

Channel access priority class (p)	m_p	$T_{mcot,p}$	**Allowed CW_p sizes**
1	2	2ms	{3, 7}
2	2	4ms	{7, 15}
3	3	6 or 10ms	{15, 31, 63, 127, 255, 511, 1023}
4	7	6 or 10ms	{15, 31, 63, 127, 255, 511, 1023}

In unlicensed spectrum, a transmitter must do LBT procedures to sense and acquire an idle channel before transmitting. LBT Type 1 channel access procedures are done by the transmitter to obtain a new COT (duration of maximum channel occupancy time (MCOT) is $T_{mcot,p}$ in Table I and Table II). After obtaining a channel, the transmitter transmits data within COT. Type 1 channel access procedures have two steps [5]. In the first step called initial Clear Channel Assessment (iCCA), the transmitter senses the channel in a defer duration T_d to be

$$T_d = t_f + m_p \times t_{sl}. \tag{1}$$

where t_f is 16 μs, t_{sl} is 9 μs that is duration of a sensing slot. m_p is the number of consecutive sensing slots depending on channel access priority class p defined in Table I and Table II.

After sensing the channel to be idle during a defer duration T_d, the transmitter performs an extended Clear Channel Assessment (eCCA) in the second step. The transmitter senses the channel in N additional sensing slots. The counter N is a random number uniformly distributed between 0 and CW_p where CW_p is the value of contention window size in Table I and Table II. The size of CW_p is set to be the smallest allowed value in a priority channel access class and might be increased to a next higher allowed value depending on the percentage of ACK feedback corresponding to the latest transmission burst that ACK feedback is available.

In each sensing slot, if the transmitter senses an idle channel, it decrements the counter by 1. If the transmitter senses a busy channel in a sensing slot, it goes to a defer stage. In this stage, it senses the channel in an additional defer duration. The transmitter exits this stage and decrements the counter by 1 if the channel is sensed to be idle during all sensing slots of the additional defer duration. Otherwise, the transmitter is still in the deferring stage and has to sense the channel in another defer duration. When the counter reaches 0, the transmitter can transmit the packet and occupy channel in a duration of MCOT.

Markov chain for Type 1 channel access procedures is shown in Fig. 1.

At each transmission by a transmitter, regardless of the number of retransmissions, the probability that the channel is sensed to be busy in a sensing slot is assumed to be p_c. The probability that the channel is sensed to be idle in a sensing slot is $p_t = 1 - p_c$.

In a t_f gap of 16 μs, energy measurement is done for a total of at least 5 μs with at least 4 μs of sensing falling within

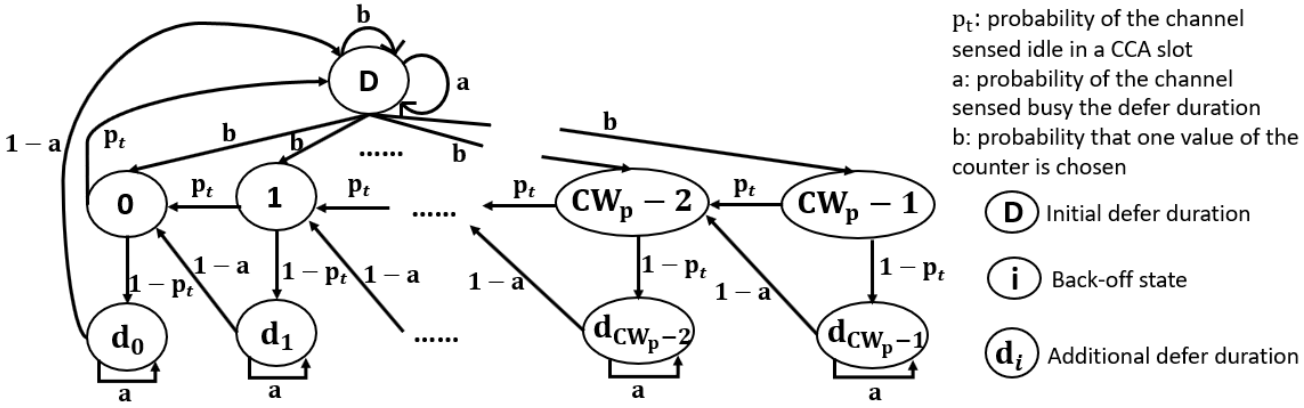

Fig. 1. Markov chain for Type 1 channel access procedures.

the sensing slot of 9 μs immediately before the transmission [5]. Therefore, the idle and busy probabilities in a t_f gap are approximated to be p_t and p_c as in a sensing slot of t_{sl}, respectively.

In the Markov chain in Fig. 1, $a = 1 - p_t^{m_p+1}$ is the probability that the channel is busy in one of the sensing slots of the defer duration. Thereby, a is the probability of sensing a busy channel in a defer duration. $b = \frac{1-a}{CW_p+1}$ is the probability that one value of the counter N is chosen after the initial successful defer duration.

B. Probabilities of the states in Markov chain for Type 1 channel access procedures

We denote π_D, π_i, π_{d_i} where $i \in [0, CW_p - 1]$ to be stationary distribution of Markov chain in Fig. 1.

For the probability of the defer states from π_{d_0} to $\pi_{d_{CW_p-1}}$, we have

$$\pi_{d_i} = \frac{1-p_t}{1-a}\pi_i \qquad i \in [0, CW_p - 1]. \tag{2}$$

For the probability of the initial defer state π_D, we have

$$\pi_D = \frac{1}{1-a-b}\pi_0. \tag{3}$$

For the probability of the back-off states from π_0 to π_{CW_p-1}, we have

$$\pi_i = (1 - \frac{bi}{1-a-b})\pi_0 \qquad i \in [0, CW_p - 1]. \tag{4}$$

By applying the normalization condition, we have

$$\begin{aligned} 1 &= \pi_D + \sum_{i=0}^{CW_p-1} \pi_i + \sum_{i=0}^{CW_p-1} \pi_{d_i} \\ &= \frac{1}{1-a-b}\pi_0 + (1 + \frac{1-p_t}{d})\times \\ &\times (CW_p - \frac{b}{1-a-b}\frac{CW_p(CW_p-1)}{2})\pi_0. \\ \Longleftrightarrow \pi_0 &= (\frac{1}{1-a-b} + (1 + \frac{1-p_t}{d})\times \\ &\times (CW_p - \frac{b}{1-a-b}\frac{CW_p(CW_p-1)}{2}))^{-1}. \end{aligned} \tag{5}$$

From (2) to (5), we can calculate the probabilities of all states in Markov chain.

The transmitter transmits in a transmission occasion if the counter N is chosen randomly to be 0 immediately after the initial defer duration or a value N different to 0 is chosen randomly then the counter reaches zero after the back-off states. The probability that a transmitter transmits in a transmission occasion is

$$\begin{aligned} P_{Tx} &= \pi_0 + b\pi_D \\ &= (1 + \frac{b}{1-a-b})\pi_0. \end{aligned} \tag{6}$$

We consider a system with H transmitters. A transmitter of interest encounters an idle channel in a sensing slot when no transmitter out of $H-1$ transmitters transmits in that sensing slot. We have the relation between p_t and P_{Tx}

$$p_t = (1 - P_{Tx})^{H-1}. \tag{7}$$

From (5) to (7), we can calculate p_t and P_{Tx}.

C. Transmitter's average channel access time in Type 1 channel access procedures

Based on the model of Type 1 channel access procedures in Section II-A, the closed-form expression of the average time that a transmitter needs to access a channel in unlicensed spectrum at different probabilities p_t is derived.

In a defer duration, if the transmitter senses a channel and detects a busy sensing slot, it considers a busy defer duration and gets out of that defer duration then moves to sense another defer duration. We have T to be the average time that the transmitter spends in a busy defer duration:

$$\begin{aligned} T = (1-p_t)t_f + p_t(1-p_t)(t_f + t_{sl}) + \\ + p_t^2(1-p_t)(t_f + 2t_{sl}) + ... + p_t^{m_p}(1-p_t)(t_f + m_p t_{sl}). \end{aligned} \tag{8}$$

When a transmitter senses the channel in the defer duration, taking into account time spent in busy defer duration, the average time spent by the transmitter until it senses an idle defer duration (the channel is idle in the t_f gap and and all t_{sl} slots) and get out of the deferring state is

$$\begin{aligned}T_{D-out} &= p_t^{m_p+1}T_d + p_t^{m_p+1}(1-p_t^{m_p+1})(T_d+T)+\\&+p_t^{m_p+1}(1-p_t^{m_p+1})^2(T_d+2T)+...\\&= p_t^{m_p+1}T_d(1+(1-p_t^{m_p+1})+(1-p_t^{m_p+1})^2+...)+\\&+p_t^{m_p+1}T((1-p_t^{m_p+1})+2(1-p_t^{m_p+1})^2+...)\\&= \frac{p_t^{m_p+1}T_d}{1-(1-p_t^{m_p+1})}+\frac{(1-p_t^{m_p+1})T}{p_t^{m_p+1}}\\&= T_d+\frac{T}{p_t^{m_p+1}}-T.\end{aligned} \tag{9}$$

The counter N decreases one unit in two cases. The first case is when the transmitter senses an idle channel in a sensing slot. The second case is when the transmitter senses a busy channel in a sensing slot then senses the channel to be idle in an additional defer duration. The average time for the counter to decrease 1 unit is

$$T_{1-backoff} = p_t t_{sl} + (1-p_t)(t_{sl}+T_{D-out}). \tag{10}$$

N is distributed uniformly between 0 and CW_p so the average value of N is

$$\tilde{N} = \frac{CW_p}{2} \tag{11}$$

The average time of the eCCA that the transmitter decrements the counter to 0 and acquires channel to transmit data is:

$$T_{all-backoff} = \frac{CW_p}{2}(p_t t_{sl} + (1-p_t)(t_{sl}+T_{D-out})). \tag{12}$$

Type 1 channel access procedures consists of the iCCA and eCCA so the average time that the transmitter spends for Type 1 channel access procedures is

$$T_{LBT} = T_{D-out} + T_{all-backoff}. \tag{13}$$

D. DL and UL transmissions' latency in unlicensed spectrum

Type 1 channel access procedures' average time in (13) is applied to calculate DL and UL transmission time in unlicensed spectrum.

If the transmitter transmits a transport block and the receiver decodes correctly this transport block after one transmission, latency of the transmission in unlicensed spectrum is

$$T_{Tx} = T_{LBT} + T_{align} + T_{trans} + T_{gNB} + T_{UE}. \tag{14}$$

where T_{LBT} is time for channel access procedures at the transmitter, T_{align} is the alignment delay, T_{trans} is time length of a transmission occasion, T_{gNB} are T_{UE} are the processing time at the gNB and the UE.

When a packet arrives, it must wait until the beginning of a transmission occasion to be transmitted. The alignment delay is uniformly distributed among the symbols between two consecutive transmission occasion. Thus, T_{align} is $\frac{TTI}{2}$ where TTI is a transmission time interval. T_{trans} is one TTI for one transmission.

(14) provides latency of a single shot transmission for both DL and UL with any set of parameters specified in the system.

In DL transmission, transmission time for an initial transmission and a retransmission is

$$T_{Tx\_DL} = 2T_{Tx} + T_{HARQ}. \tag{15}$$

We have T_{HARQ} to be

$$T_{HARQ} = T_{LBT\_Type2} + T_{K1} + T_{UE} + T_{trans} + T_{gNB}. \tag{16}$$

where T_{LBT_Type2} is 25 μs that is the sensing duration of Type 2 channel access procedures defined in [5]. T_{K1} is the duration from the end of DL data to the beginning of feedback occasion.

The UE might be configured to transmit K repetitions of a transport block in the consecutive transmission occasions without feedback. This configuration increases the transmission time and processing time so margin to latency requirement decreases. Transmission time of an UL transmission with K repetitions is

$$T_{Tx\_UL} = T_{LBT} + T_{align} + K \times T_{trans} + K \times T_{gNB} + T_{UE}. \tag{17}$$

(17) reflects time that the UE spends with CG transmission when it does not take into account SR and UL grant.

To satisfy URLLC latency requirement, T_{Tx}, T_{Tx_DL} and T_{Tx_UL} must be smaller than 1 ms so it leads to constraint on T_{LBT} that the UE can spend for channel access procedures.

III. Conditions and Enhancements in Using Type 1 Channel Access Procedures

Based on (13), the average time delay in Type 1 channel access procedures T_{LBT} is calculated. Fig. 2 shows the average time delay that the gNB needs to access the channel in DL transmission with 4 priority classes in Table I. Fig. 3 shows the average time delay that the UE needs to access the channel in UL transmission with 4 priority classes in Table II. When priority classes 3 and 4 are used, even only time delay in Type 1 channel access procedures exceeds the latency budget of 1 ms with low probability of sensing idle channel p_t.

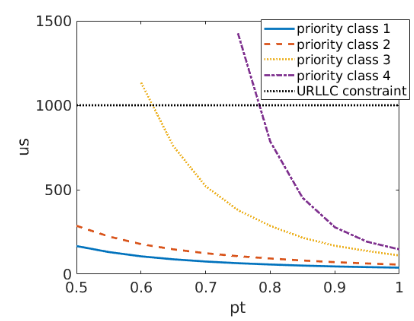

Fig. 2. Type 1 channel access procedures average time in DL transmission.

Fig. 4 shows DL transmission time with an initial transmission and a retransmission as expressed in (15). TTI is 2 OFDM symbols. SCS is 30 kHz. The processing time at the gNB and the UE is 1 TTI. URLLC requirement of 1 ms is only met with the probability of sensing idle channel bigger than 0.7 for channel access priority class 1, 0.85 for channel access priority class 2.

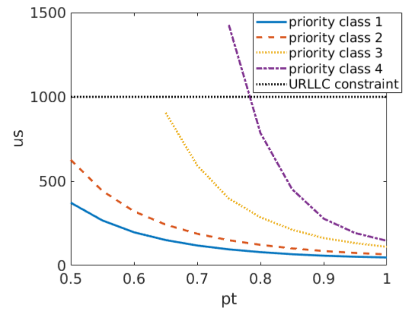

Fig. 3. Type 1 channel access procedures average time in UL transmission.

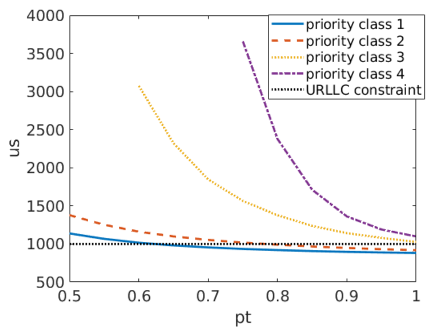

Fig. 4. Total transmission time in DL transmission with an initial transmission and a retransmission in SCS of 30kHz.

Fig. 5 shows DL transmission time with an initial transmission and a retransmission similar to Fig. 4 but SCS is 60 kHz. URLLC requirement is only met with the probability of sensing idle channel bigger than 0.5 for channel access priority class 1, 0.55 for channel access priority class 2, 0.85 for channel access priority class 3, 0.9 for channel access priority class 4.

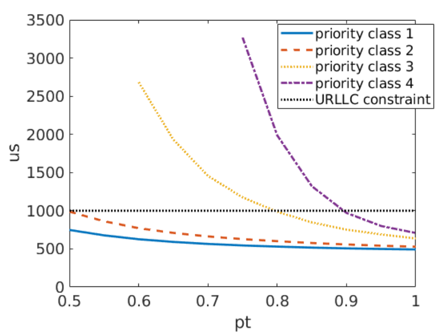

Fig. 5. Total transmission time in DL transmission with an initial transmission and a retransmission in SCS of 60kHz.

Fig. 6 shows the total UL transmission time as expressed in (17). TTI is 2 OFDM symbols. SCS is 30 kHz. The processing time at the gNB and the UE is 1 TTI. The UE is configured to transmit 4 repetitions of a TB in 4 consecutive TTIs.

From Fig. 6, to meet latency budget of 1 ms, the probability of sensing idle channel must be bigger than 0.55 for channel access priority class 1, 0.65 for channel access priority class 2, 0.85 for channel access priority class 3, 0.9 for channel access priority class 4.

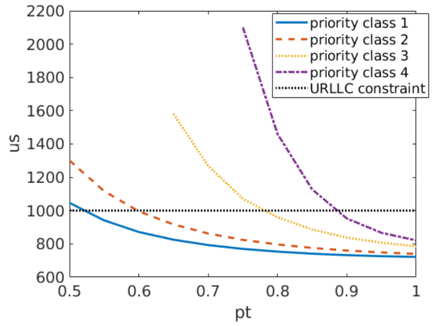

Fig. 6. Total transmission time in UL transmission with 4 repetitions in SCS of 30kHz.

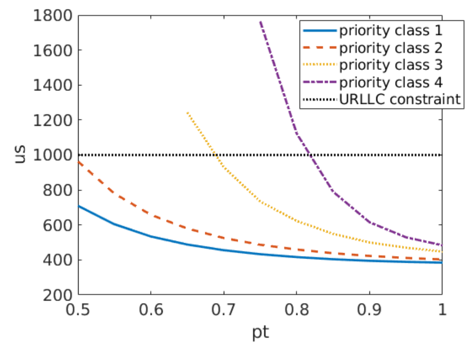

Fig. 7. Total transmission time in UL transmission with 4 repetitions in SCS of 60kHz.

Fig. 7 shows the total UL transmission time of a transmission with 4 repetitions in SCS of 60 kHz. To meet 1 ms, the probability of sensing idle channel must be bigger than 0.65 for channel access priority class 2, 0.7 for channel access priority class 3, 0.85 for channel access priority class 4.

As can be seen in Fig. 4, Fig. 5, Fig. 6 and Fig. 7, channel access priority classes 3 and 4 cause high latency in channel access and are not suitable for URLLC, especially with low probability of sensing idle channel. However, at this moment, channel access priority class is not dedicated to the specific services. Therefore, different channel access priority classes are proposed to be used for different services. Priority classes 3 and 4 in Table I and Table II that provide longer COT but higher latency of channel access are assigned to Enhanced Mobile Broadband (eMBB) service because eMBB deals with the transmission with high payload without latency constraint. URLLC focusing on short time transmission is assigned to use priority classes 1 and 2 in Table I and Table II due to its shorter channel access time. Furthermore, URLLC with latency requirement of 1 ms does not need long COT. In DL transmission, the gNB chooses priority class dedicated to the arrival data of URLLC or eMBB service so that it can access the channel and transmit data within the allowed requirements. In UL transmission, the UE distinguishes eMBB and URLLC to choose the appropriate priority class by decoding priority class field in UL grant from the gNB. When the gNB sends UL grant to schedule an UL transmission, it includes bits in UL grant to make the UE know the priority class of the transmission. In Type 1 CG transmission, all transmission parameters are configured by Radio Resource Control (RCC) signaling and there is no UL grant or activation downlink control channel (DCI). In this case, the dedicated priority class for a specific service is configured by a RRC parameter.

Based upon the simulation results and prior discussion, we propose to define new set of access classes which are suitable for URLLC services, in terms of their physical characteristics and quality of service requirements. COT for priority classes dedicated to URLLC is assigned new values being smaller than the existing values. URLLC latency budget is 1 ms so COT in priority classes dedicated to URLLC should not be larger than 1 ms. A shorter COT reduces delay for other UEs in the system so the use of these new priority classes become fairer to the co-channel UEs. A smaller value of m_p is used in new priority classes for UL. New tables of channel access priority class with new entries dedicated to URLLC are shown in Table III and Table IV. New added entries are highlighted in bold text. When Table III and Table IV are used, priority class 1, 2, 4, and 5 are assigned to URLLC service. The priority class chosen by the gNB is based in the channel condition of the probability of sensing idle channel to satisfy the URLLC latency requirement and guarantee a fair use of channel with other UEs by using a suitable COT.

TABLE III
NEW CHANNEL ACCESS PRIORITY CLASS FOR DL

Channel access priority class	m_p	$T_{mcot,p}$	**allowed** CW_p **sizes**
1	**1**	**0.5ms**	**{3, 7}**
2	**1**	**1ms**	**{3, 7}**
3 (original priority class 1)	1	2ms	{3, 7}
4	**1**	**0.5ms**	**{7, 15}**
5	**1**	**1ms**	**{7, 15}**
6 (original priority class 2)	1	3ms	{7, 15}
7 (original priority class 3)	3	8 or 10ms	{15, 31, 63}
8 (original priority class 4)	7	8 or 10ms	{15, 31, 63, 127, 255, 511, 1023}

TABLE IV
NEW CHANNEL ACCESS PRIORITY CLASS FOR UL

Channel access priority class	m_p	$T_{mcot,p}$	**allowed** CW_p **sizes**
1	**1**	**0.5ms**	**{3, 7}**
2	**1**	**1ms**	**{3, 7}**
3 (original priority class 1)	2	2ms	{3, 7}
4	**1**	**0.5ms**	**{7, 15}**
5	**1**	**1ms**	**{7, 15}**
6 (original priority class 2)	2	4ms	{7, 15}
7 (original priority class 3)	3	6 or 10ms	{15, 31, 63, 127, 255, 511, 1023}
8 (original priority class 4)	7	6 or 10ms	{15, 31, 63, 127, 255, 511, 1023}

Fig. 8 compares total UL transmission time with 4 repetitions in SCS of 30 kHz between the use of original URLLC dedicated priority class 1, 2 in Table II and the use of new URLLC dedicated priority class 1, 4 in Table IV. As can be seen, new priority classes bring a shorter transmission time and guarantee latency of 1 ms even with low probability of idle channel p_t.

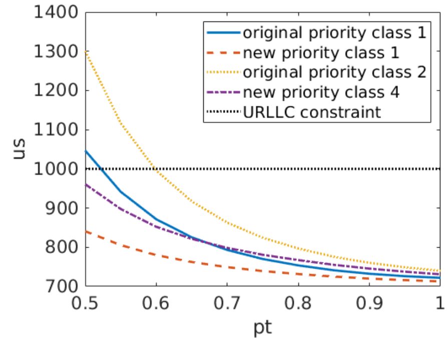

Fig. 8. Comparison of total transmission time between original priority class and new priority class in UL transmission with 4 repetitions in SCS of 60kHz.

Acknowledgments

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IV. Conclusion

This paper presented Markov chain model for Type 1 channel access procedures in unlicensed spectrum and calculated the probability of each state and transmission probability. A closed-form expression of average time delay of Type 1 channel access procedures is derived and used to calculate DL and UL transmission time in unlicensed spectrum where channel access delay has an impact. To satisfy URLLC requirements, the specific priority classes are dedicated to URLLC service. The entries in Type 1 channel access procedures' tables are extended to distinguish and serve better different services.

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