Enhancements of PUSCH repetitions for URLLC in licensed and unlicensed spectrum

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***Abstract*—Ultra-reliable low-latency communication (URLLC) is specified in 5G New Radio to serve the applications and services with the strict requirements of reliability and latency. The URLLC operation is in licensed spectrum then extended to unlicensed spectrum to support new use cases in the industrial scenario. This requires new features in physical layer to make URLLC work with the strict requirements in both licensed and unlicensed spectrum.**

This paper focuses on the design of physical uplink shared channel (PUSCH) repetitions for URLLC. In PUSCH repetition, the nominal PUSCH repetitions might be segmented into the smaller actual repetitions due to uplink/downlink (UL/DL) directions in time division duplex (TDD) configuration or slot boundary. This segmentation causes a degradation of the URLLC performance due to a smaller number of valid symbols for PUSCH repetitions, a drop of the repetition in an orphan symbol and an increase of listen before talk (LBT) overhead.

To enhance the URLLC performance, two schemes are proposed. The first scheme deals with segmentation due to UL/DL directions by dynamically switching the chosen semi-static DL symbols to UL symbols. The second scheme deals with orphan symbols by transmitting signal in these symbols in order to maintain a continuous PUSCH transmission and avoid an additional LBT. The results show an improvement of URLLC performance in licensed and unlicensed spectrum by applying these two schemes.

***Index Terms*—5G, URLLC, unlicensed spectrum, listen before talk, PUSCH repetitions, time division duplex, orphan symbol**

I. Introduction

A. Ultra-reliable low-latency communication

Ultra-reliable low-latency communication (URLLC) has become one of the main studies of the 3rd Generation Partnership Project (3GPP) since Release 15. The goal of URLLC is to serve the services and applications with the strict reliability and latency requirements such as industrial Internet of Things, autonomous vehicles, remote surgery. 3GPP defines the target for the URLLC scenario 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".

B. Physical uplink shared channel repetition for URLLC in licensed spectrum

The strict requirements of URLLC requires the improvements in physical layer design. In uplink (UL) transmissions, there are two types of transmission: dynamic grant (DG) and configured grant (CG) transmission. In DG transmission, the user equipment (UE) sends scheduling request (SR) to the base station (gNB) and receives UL grant with resource allocation. In CG transmission, the UE transmits UL data in the configured resources without the transmission of SR and UL grant so the use of CG transmission reduces latency. There are two types of CG configuration. In Type 1 CG, a radio resource control (RRC) signalling indicates the full time domain resource allocation including periodicity, offset, start symbol and length of PUSCH and K repetitions over K slots/sub-slots ($repK$) without any signalling of physical layer such as downlink control information (DCI). In Type 2 CG, only periodicity and $repK$ are given through RRC signalling. The other time domain related parameters are given through the activation DCI [3].

In both DG and CG transmission, one physical uplink shared channel (PUSCH) transmission instance is not allowed to cross the slot boundary. Therefore, to avoid transmitting a long PUSCH across slot boundary, the UE can transmit small PUSCHs in several repetitions scheduled by an UL grant or RRC in the consecutive available transmission occasions. The use of PUSCH repetitions for one transport block (TB) also reduces latency and increases reliability of PUSCH transmission where a UE can be configured to transmit a number of repetitions across consecutive transmission occasions without feedback. In PUSCH repetition Type A, each slot contains only one repetition and the time domain for the repetitions of a TB is the same in those slots. In PUSCH repetition Type B, the repetitions are carried out in the consecutive mini-slots so one slot might contain more than one repetition of a TB. The repetitions might be segmented into smaller repetitions due to slot boundary, downlink (DL) symbols and the symbols in the invalid pattern [3].

C. URLLC in unlicensed spectrum

With new use cases in the industrial scenario, URLLC is extended to unlicensed spectrum. In unlicensed spectrum, a transmitter is required to do listen before talk (LBT) to check the availability of a channel before a DL or UL transmission. If a transmitter needs to acquire a channel to initiate its own channel occupancy time (COT), Type 1 channel access procedures are used. The channel is sensed in a defer duration and multiple sensing slots of 9 μs based on a back-off process. If a transmitter uses a shared COT initiated by another transmitter to acquire a channel, Type 2 channel access procedures are used where the channel is sensed in a duration of 25 μs. If the gap between two transmission bursts in a COT is smaller than 16 us, a transmitter does not have to do LBT before transmitting the subsequent transmission [4]. The uncertainty of LBT causes latency and a decrease of transmission reliability because the packet is dropped out of URLLC latency budget. To make URLLC work and satisfy the stringent requirements in unlicensed spectrum, the enhancements in physical layer design must be done.

This paper focuses on the enhancements of PUSCH repetition Type B for URLLC in licensed and unlicensed spectrum. The problems of PUSCH repetition Type B that degrade UL transmission's performance and related works to solve these problems are presented in Section II. The proposed schemes about dynamically updating semi-static DL symbols and transmitting Demodulation Reference Signal (DMRS) in the orphan symbols are introduced in Section III. Section IV shows the results of the proposed schemes. Section V concludes this work.

II. Gap in the middle of PUSCH repetitions

A. Problem formulation

1) Gap due to UL/DL directions

In 3GPP Release 15 and 16, UL transmission of a TB is supported with multiple repetitions to achieve the strict URLLC requirements. Time domain resource is indicated for the first "nominal" repetition. The time domain resources for the remaining repetitions are derived based at least on the resources for the first repetition and UL/DL direction of symbols. The number of valid symbols for PUSCH of a TB that the UE can use are in the time window $K \times L$ where K is the number of nominal repetitions, L is the length of a nominal repetition.

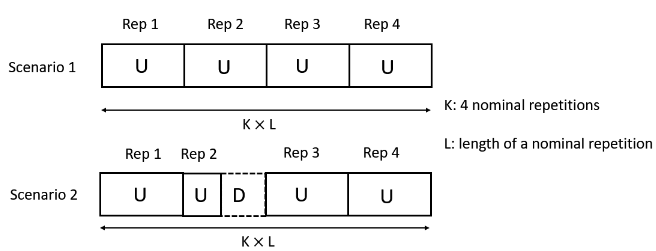

Fig. 1. UL transmission in TDD configuration licensed spectrum.

In PUSCH repetition Type B, the actual number of repetitions might be bigger than the nominal K repetitions. If a nominal repetition encounters slot boundary or DL symbols in TDD configuration, this repetition is fragmented into multiple actual repetitions. However, the time window of valid symbols is still $K \times L$ so the presence of DL symbols in the middle of PUSCH repetitions reduces the number of valid symbols for PUSCH that the UE can use in time division duplex (TDD). In Fig. 1, a part of the second repetition in scenario 2 is dropped due to DL symbols in the middle of the repetitions. This reduces reliability of UL transmission of a TB when PUSCH repetition Type B is used in licensed spectrum.

In unlicensed spectrum, when PUSCH repetition Type B is used, the interruption in UL transmission of the repetitions even has a bigger impact due to LBT overhead. Fig. 2 shows two scenarios of UL transmission of a TB in TDD configuration in unlicensed spectrum. In both scenarios, the UE is scheduled by the gNB to transmit 4 nominal repetitions in Type B (DG or CG transmission). The time window within which valid symbols are used for transmission is $K \times L$ where K is 4 nominal repetitions, L is the length of a nominal repetition. Before the transmission, the UE must do LBT Type 1 to acquire the channel and it is allowed to use this channel in COT duration. This COT is shared with the gNB so the gNB can transmit DL data in DL symbols within this COT. Depending on the gap between DL and UL bursts, the gNB would transmit without or with LBT Type 2 channel access procedures.

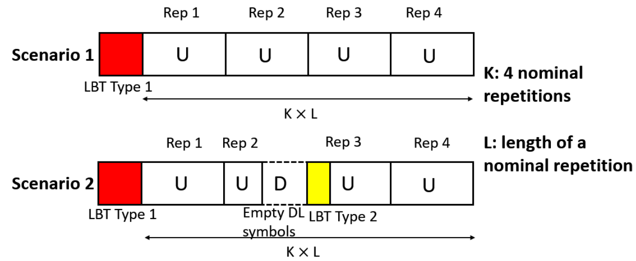

Fig. 2. UL transmission in TDD configuration unlicensed spectrum.

In scenario 1, there are 4 consecutive UL sub-slots so the UE can transmit the whole 4 repetitions without an interruption after a successful LBT Type 1. However, in scenario 2, due to the URLLC latency budget of 1 ms, the UL repetitions must be scheduled in the UL resources segmented by the DL sub-slots when the transmission cannot wait the next continuous UL sub-slots for all repetitions. The UL transmission is interrupted because of DL symbols in the middle of the second repetition. The UE cannot transmit UL data in a DL transmission occasion so the second repetition is fragmented into 2 actual repetitions. With sub-carrier spacing (SCS) from 15 kHz to 120 kHz and a sub-slot of 2, 4, 7 symbols, the time length of DL sub-slot is larger than 16 μs. In some cases, DL symbols are configured in a semi-static way in advance. If the gNB does not have DL data to transmit at those semi-static DL symbols, there will be a gap between two UL bursts. When the gap between two UL transmission occasions is larger than 16 μs due to the empty semi-static DL symbols, the UE must do an additional LBT Type 2 to continue to transmit the remaining repetitions in the UE-initiated COT. This additional LBT Type 2 consumes at least 25 μs or more if the channel is busy. The time window $K \times L$ is fixed so an increase of LBT time reduces time of data transmission. The UE transmits less data in the repetition than configured that causes a decrease of reliability.

2) Gap due to orphan symbols

The gap in the transmission of PUSCH repetitions Type B is also caused by orphan symbols. In scenario 2 of Fig. 3, two repetitions Type B of a TB are scheduled. Each repetition has 4 symbols. After the first repetition, the second repetition is fragmented by the slot boundary between slot 1 and slot 2. There is one symbol (orphan symbol) in slot 1 and 3 symbols

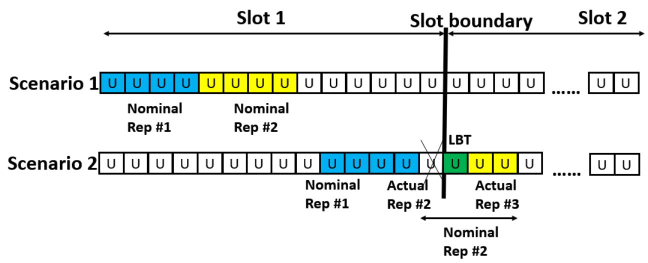

Fig. 3. Interruption in the transmission of UL repetitions due to orphan symbol in unlicensed spectrum.

in slot 2. However, an actual repetition with a single symbol is not transmitted [3]. Thus, the UE does not transmit a repetition in the last symbol of slot 1 and this symbol is empty. The UE only starts to transmit the second repetition from the first symbol of slot 2. It creates a gap of one symbol between two repetitions. With SCS from 15 kHz to 60 kHz, the length of a symbol is larger than 16 μs. Therefore, in unlicensed spectrum, at least, a short LBT of 25 μs is needed before the transmission of the second repetition. It causes LBT overhead and reduces the time interval that the UE can transmit the second repetition.

B. Related works

In [6], PUSCH repetition Type B is harmonized with CG PUSCH in unlicensed spectrum but there is no technique to avoid the gap in PUSCH repetitions.

In [7] and [8], the time window within which valid symbols are used for PUSCH transmission is extended to be longer than $K \times L$ at least in case of semi-static DL symbols. The extension of the time window of a transmission might cause a delay of the next transmission or collision with other UE. Moreover, this extension may cause ambiguity on the ending of the window if the UE misses the dynamic signal to update the flexible symbols in dynamic channel configuration.

In [9], the UE is proposed to transmit the last symbol of the repetition before the orphan symbol or the first symbol of the repetition after the orphan symbol instead of leaving an empty orphan symbol. It helps the UE to keep the channel but changes code rate of the repetitions.

In [10], the number of UL and DL symbols in TDD configuration is calculated based on the arrival rates of DL and UL data. It mitigates DL symbols in the middles of PUSCH repetitions but cannot avoid entirely the problem of gap between UL bursts.

III. Enhancements of PUSCH repetitions in licensed and unlicensed spectrum

A. Handling gap due to UL/DL directions

In TDD configuration, DL symbols might be configured in a semi-static way so that the gNB can transmit DL data (physical downlink control channel (PDCCH), physical downlink shared channel (PDSCH), synchronization signal block (SSB)). In case the gNB must schedule a PUSCH transmission with DL symbols between the repetitions in Scenario 1 of Fig. 4 due to time constraint of URLLC, the semi-static DL symbols cause a segmentation in the PUSCH repetitions even if the gNB has no DL data to transmit in that occasion. This DL occasion is scheduled in a semi-static way in advance so the gNB does not know whether it has DL data at that occasion or not. Therefore, when the gNB schedules the repetitions of PUSCH, if it recognizes that it does not have DL data to transmit in the DL symbols causing segmentation, it switches semi-static DL symbols to UL symbols as in Scenario 2 of Fig. 4. This scenario is for a transmission in unlicensed spectrum. There are two benefits of this switch. Firstly, the UE can transmit PUSCH repetitions without segmentation so that the valid symbols for UL transmission is ensured to be $K \times L$ symbols where K is the number of nominal repetitions, L is the length of a nominal repetition. Secondly, no additional LBT Type 2 is required due to segmentation. As can be seen in Fig. 4, the UE can transmit full data in the second and third repetitions in Scenario 2 instead of dropping a part of the second and third repetitions in Scenario 1.

The update of empty semi-static DL symbols to UL symbols is also applied to the PUSCH repetitions in licensed spectrum so the UE can transmit all full repetitions as configured in the time window without segmentation and dropping data in DL symbols to guarantee reliability.

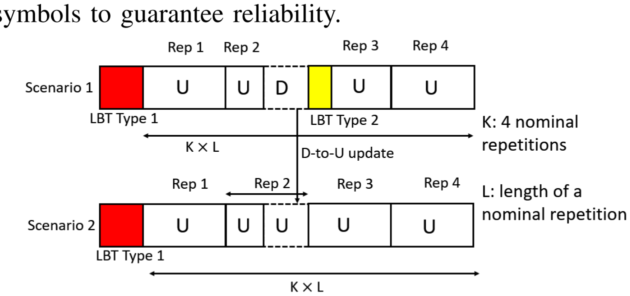

Fig. 4. Semi-static DL symbols are switched to UL symbols.

In case the gNB has DL data to transmit in the semi-static DL symbols among the UL symbols that it intends to schedule to an UL transmission, if the UL data has higher priority than DL data, the gNB also switches semi-static DL symbols to UL symbols and delays DL transmission to the next occasion so that the UE can transmit a continuous high priority UL transmission. As in Fig. 4, if DL symbols contain low priority transmission compared to UL transmission, these DL symbols are switched to UL symbols.

The update of the chosen semi-static DL symbols to UL symbols are applied to both DG and CG transmission. For DG transmission, after the gNB decides the semi-static DL symbols that are switched to UL symbols, when the gNB sends UL grant to schedule PUSCH repetitions, it also sends a dynamic slot format indicator (SFI) signal such as DCI format 2_0 to the UE to switch the chosen DL symbols in the middle of PUSCH repetitions to UL symbols. The gNB also can indicate the update of semi-static DL symbols to UL symbols to the UE in the UL grant DCI by using one additional bit. Another way is to indicate implicitly through priority index in UL grant DCI. The UE that is scheduled with high priority UL transmission uses the semi-static DL symbols to transmit

PUSCH. The gNB knows that pre-configuration so it does not transmit DL data in those symbols.

For CG transmission, after activating CG configurations, the gNB can send periodically DCI format 2_0 or a RRC signal to switch the chosen DL sub-slots/slots to UL sub-slots/slots. The period of DCI format 2_0 or RRC signal depends on priority of the CG configurations, the arrival rate of UL data at the UE using the configurations and the arrival rate of DL data at the gNB.

The method to update semi-static DL symbols can be extended to update semi-static UL symbols. This means that the gNB can update semi-static UL symbols to DL symbols to use in DL transmission. It is useful when the gNB has a high arrival rate of URLLC DL data and needs to use the updated symbols to meet URLLC requirements for DL transmission. The gNB sends dynamic SFI to notify the UE about the update of semi-static UL symbols to DL symbols so that the UE decodes DL transmission in these symbols instead of transmitting UL data.

In dynamic configuration, a symbol can be configured as a semi-static flexible symbol then is updated dynamically to UL or DL symbol by DCI format 2_0 indicating SFI from the gNB to the UE. For CG transmission in licensed and unlicensed spectrum, if dynamic SFI is configured but the UE cannot decode DCI format 2_0 indicating SFI to update the semi-static flexible symbols due to channel condition, an actual PUSCH repetition in those non-updated flexible symbols is dropped. This causes a decrease of PUSCH transmission' reliability.

To increase reliability of URLLC UL transmission, if dynamic SFI is not received, the UE will use the semi-static flexible symbols in the scheduled resource as the UL symbols to transmit the high priority repetitions without any gap instead of dropping the repetitions in those symbols. In other words, a repetition is not fragmented around the semi-static flexible symbols or dropped because of a conflict with the semi-static flexible symbols but an actual repetition is transmitted continuously in time in that case. Therefore, in both licensed and unlicensed spectrum, the configured number of repetitions is ensured. Moreover, in unlicensed spectrum, no additional LBT is required due to the dropped repetition in the middle of the transmission of PUSCH repetitions.

B. Handling orphan symbols

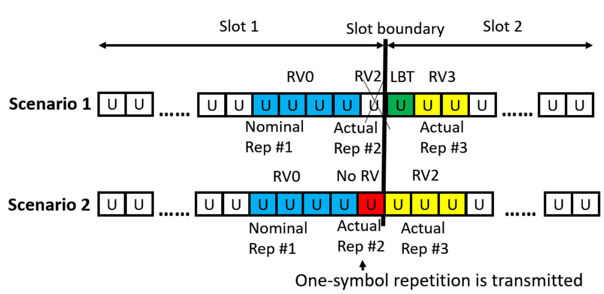

Fig. 5. Orphan-symbol actual repetition containing DMRS is transmitted in unlicensed spectrum.

An actual PUSCH repetition in an orphan symbol due to segmentation is dropped that causes a gap between two burst of PUSCH repetitions. In unlicensed spectrum, the presence of this gap leads to LBT overhead in PUCSH transmission. To guarantee the performance of high priority transmission as URLLC, the discontinuous PUSCH repetition's transmission due to one-symbol fragment must be avoided.

In the proposed scheme, the UE still transmits the one-symbol repetition so the transmission of PUSCH repetitions is continuous and LBT Type 2 channel access procedures after one-symbol fragment is not required before the UE continues to transmit the PUSCH repetitions as shown in Fig. 5. Thanks to a continuous channel without LBT, the UE has more symbols in the scheduled time window to transmit PUSCH repetitions so that PUSCH transmission of a TB attains a higher reliability. The transmission of one-symbol repetition is initiated based on priority of the transmission.

The one-symbol repetition contains only DMRS and does not contain any TB data. The transmission of additional DMRS provides an opportunity to do channel estimation. It improves the performance of high priority UL transmission. Because this one-symbol repetition does not contain data, it is not taken into account in the calculation of redundancy version (RV) sequence of the repetitions as shown in Fig. 5. With a RV sequence of $\{0, 2, 3, 1\}$, in Scenario 2, only the first and third repetitions have RVs to be 0 and 2, respectively, while the second repetition is not assigned RV. In other words, the one-symbol repetition is transmitted but not considered as an actual repetition.

To indicate the activation of a transmission in an orphan symbol, in UL DG transmission, the gNB adds one bit to UL grant DCI. This bit tells the UE to transmit DMRS in the one-symbol fragment or drop the transmission in the orphan symbol. If UL transmission is high priority with the strict requirements as URLLC, DMRS transmission on one–symbol repetition is activated. Otherwise, the transmission of one-symbol repetition is not activated.

In UL CG transmission, the transmission of DMRS in the one-symbol fragment to avoid LBT is activated by a new RRC parameter for Type 1 CG or 1 bit in the activation DCI in Type 2 CG.

The transmission of one-symbol repetition also can be indicated implicitly to the UE by high priority index in DCI or RRC. When DCI or RRC contains high priority index for a PUSCH transmission, by pre-configuration, the UE transmits one-symbol repetition instead of dropping it. Otherwise, the UE does not transmit one-symbol repetition.

IV. SIMULATION RESULTS

A. Performance of the scheme to handle UL/DL directions

Using the parameters in Table I, the first simulation is done in licensed spectrum to compare the performance of PUSCH repetitions in the current scheme where PUSCH repetitions might be dropped because of DL symbols and in the proposed scheme where DL symbols are dynamically updated to UL symbols for PUSCH repetitions. It is set that one out of four

TABLE I
SIMULATION PARAMETERS

Parameters	Values
Waveform	CP-OFDM
Subcarrier spacing	30kHz
Channel model	Additive white Gaussian noise (AWGN)
Channel coding	Low-density parity-check (LDPC) code
TB length	160 bits
Number of repetitions/TB	4
Number of symbols/repetition	4
MCS Index	1

repetitions conflicts with one DL symbol so this repetition is not transmitted in full. As can be seen in Fig. 6, block error rate (BLER) of a repetition conflicted with DL symbol increases because only three UL symbols can be used to transmit data instead of four symbols. In the proposed scheme, the DL symbol is updated to UL symbol so the repetition is transmitted in full and has a lower BLER.

To increase reliability of PUSCH transmission, the UE combines the repetitions of a TB so that it can decode the packet with lower code rate. In Fig. 6, even with soft-combining, the performance of PUSCH transmission is still degraded due to the conflict of a repetition with a DL symbol. When DL symbol is updated to UL symbol, soft-combining of the repetitions achieves better performance.

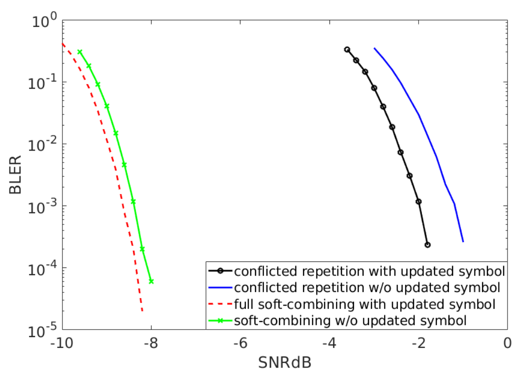

Fig. 6. Performance PUSCH repetitions in licensed spectrum with updated DL-to-UL symbol.

The second simulation is done in unlicensed spectrum to compare the current and proposed schemes. The influence of DL-UL directions is bigger in unlicensed spectrum than in licensed spectrum because the UE must do a LBT of 25 μs (equivalent to one symbol in simulation) after the empty DL symbols. Due to LBT and DL symbols, the UE has less time to transmit data in the repetitions. As can be seen in Fig. 7, when the UE decodes data by doing soft-combining of the repetitions, the BLER of PUSCH repetitions is higher in unlicensed spectrum than in licensed spectrum when a repetition collides with an empty DL symbol. The scheme of updating symbols brings more benefits to the performance of PUSCH repetitions in unlicensed spectrum.

The third simulation using the parameters in Table I is done in licensed and unlicensed spectrum to compare the

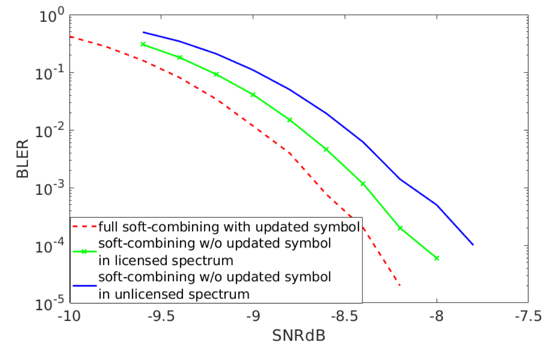

Fig. 7. Performance PUSCH repetitions in unlicensed spectrum with updated DL-to-UL symbol

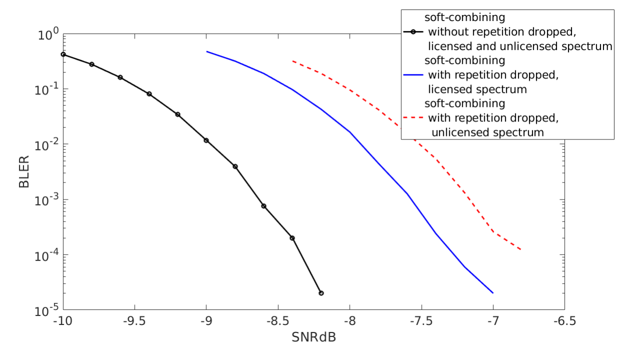

Fig. 8. Performance PUSCH repetitions in licensed and unlicensed spectrum with flexible symbols used as UL symbols

performance of PUSCH repetitions in two schemes: the conventional scheme where the PUSCH repetition is dropped in the non-updated semi-static flexible symbols and the proposed scheme where the non-updated semi-static flexible symbols are used as UL symbols to transmit PUSCH repetition. In the simulation, one out of four repetitions has the non-updated semi-static flexible symbols so this repetition is dropped in the conventional scheme and the gNB only receives 3 repetitions to do soft-combining. As shown in Fig. 8, BLER of PUSCH transmission in licensed spectrum increases when one repetition is dropped and only three repetitions are transmitted. BLER even grows more significantly for PUSCH transmission in unlicensed spectrum because the UE must consume more time for an additional LBT after dropping a repetition and has less time to transmit PUSCH repetitions. When the non-updated flexible symbols are used for UL symbols and the repetition is not dropped in the proposed scheme and the gNB receives all four repetitions for soft-combining, BLER of PUSCH transmission in both licensed and unlicensed spectrum is lower than that of the conventional scheme.

B. Performance of the scheme to handle orphan symbols

Using the parameters in Table I, the simulation is done to compare PUSCH performance in unlicensed spectrum between the conventional scheme of dropping the actual repetition in the orphan symbols and the scheme of transmitting DMRS in the orphan symbols. It is set that one repetition is segmented and creates an actual repetition in an orphan symbol. As can be seen in Fig. 9, the actual repetition is dropped and creates a gap in PUSCH repetition so the UE must consume more time for an additional LBT so it has less time to transmit data in the nominal repetition (2 symbols instead of 4 symbols). This repetition has a high BLER and becomes undecodable. A DMRS in orphan symbol helps the UE to keep channel and avoid an additional LBT so the nominal PUSCH repetition has a lower BLER. The performance of PUSCH transmission in soft-combining with DMRS in orphan symbol is also better that that of PUSCH in the conventional scheme.

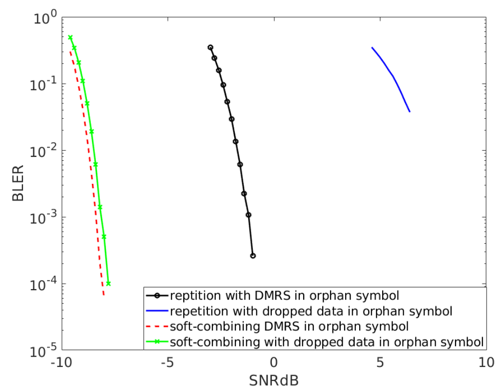

Fig. 9. Performance PUSCH repetitions in unlicensed spectrum with DMRS in orphan symbol

V. Conclusion

The work enhances the performance of PUSCH Type B repetition for URLLC in licensed and unlicensed spectrum by proposing two schemes. The first scheme about dynamically updating DL symbols to UL symbols helps PUSCH repetitions avoid the unnecessary segmentation in the middle of transmission. The second scheme about transmitting DMRS in orphan symbols helps the UE keep channel so that it can resume PUSCH transmission without an additional LBT.

Acknowledgment

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