# Outer Loop Link Adaptation Enhancements for Ultra Reliable Low Latency Communications in 5G

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***Abstract*—The very low block error rate (BLER) targets required in ultra-reliable low-latency communications (URLLC) call for new channel state information (CSI) feedback enhancements for an accurate link adaptation (LA) in the radio interface. This paper describes and analyses two new feedback reporting types, in addition to the legacy positive and negative acknowledgements (ACK/NACK) feedback, based on a form of soft-ACK reports. The aim is to improve the outer loop link adaptation (OLLA) accuracy in 5G New Radio (5G NR) based URLLC wireless communications systems where the amount of NACK events will be negligible. These schemes are based on the physical downlink data channel (PDSCH) decoding performance. In particular, the methods are based on an indication of the decoding margin of a PDSCH transmission, for the so-called Scheme A, and on an indication of the estimated block error probability (BLEP) of a PDSCH transmission, for the so-called Scheme B. In addition, two interference measurement (IM) approaches are analysed and compared based on non zero power CSI reference signal (NZP CSI-RS) and CSI interference measurement (CSI-IM) resources. The results show that Scheme A does not converge to any predefined BLER target while Scheme B allows faster convergence times towards the predefined target compared to legacy OLLA scheme. These results indicate that a new feedback reporting approach based on the estimated BLEP is suitable to achieve the tight latency requirements in URLLC scenarios together with efficient radio link performance.**

***Keywords*—5G new radio (NR), link adaptation (LA), outer loop link adaptation (OLLA), soft-Ack reporting, interference measurements, ultra reliable low latency communications (URLLC)***

## I. Introduction

The fifth generation New Radio (5G NR) mobile networks comprise diverse use scenarios while being mainly developed for the three service types [1], namely, enhanced mobile broadband (eMBB), massive machine-type communications (mMTC) and ultra-reliable low-latency communications (URLLC). The achievable latency and reliability performance of NR are key aspects to support use cases with tighter requirements such as automated factory processes, augmented reality in heath-care services and industries, or intelligent transport systems among others. In this context, link adaptation (LA) techniques are widely used to determine an accurate modulation and coding scheme (MCS) based on channel quality indicator (CQI) reports from the user equipment (UE) [2], [3]. However, these reports may be inaccurate and outdated due to the inherently varying channel conditions and interference from neighbouring cells. An outer loop link adaptation (OLLA) scheme is commonly used to cope with CQI inaccuracies and adjust the MCS selection based on the hybrid automatic repeat request (HARQ) feedback [4]. The estimated signal-to-noise-ratio (SINR) values are continuously adjusted by an OLLA offset based on positive and negative acknowledgements (ACK/NACK) sent by the UE. One of the issues of a binary HARQ feedback is the slow convergence of the OLLA algorithm. This scheme may fulfill the requirements in eMBB usage scenarios, but due to the very low block error rate (BLER) targets in URLLC scenarios (as low as $10^{-9}$), the sparse NACK occurence becomes a major issue to steer OLLA and new approaches should thus be investigated.

There are several studies in the literature proposing channel state information (CSI) feedback enhancements for accurate LA. For instance, new CQI reporting schemes for LA are proposed to instantaneously track the interference variations at UE side based on the experienced SINR [5], [6]. Besides, there have been some attempts to deal with OLLA convergence issues, such as an enhanced OLLA scheme that dynamically adjusts the OLLA step size which was proposed in [7], or more recently, reinforcement learning to fine-tune OLLA parameters based on the ACK/NACK feedback that was investigated in [8]. In order to support OLLA operation for the very low BLER targets in URLLC scenarios, the focus of this study is on new reporting metrics that may help to provide continuous feedback to the base station (gNB) to adjust OLLA more frequently. In particular, new soft-ACK reporting types can be triggered by successful reception of the physical downlink data channel (PDSCH). One of the main advantages of soft-ACK feedback types is that OLLA can be adjusted already before PDSCH decoding errors take place. In that regard, physical layer feedback enhancements for meeting URLLC requirements have been discussed in the latest 3rd Generation Partnership Project (3GPP) specifications in Release 17, see [9], and are taken as baseline in this study. Specifically, we analyse and evaluate two feedback reporting types to improve OLLA accuracy and the corresponding convergence times. These schemes are based on an indication of the decoding margin of a PDSCH transmission, and an indication of the estimated block error probability (BLEP) of a PDSCH transmission, respectively.

Link level simulations are used to evaluate the performance of the PDSCH channel, where the model consists of one serving cell and two interfering cells. Two different interference measurement methods are also investigated, where the interference measurements rely on the CSI feedback carried out on the CSI reference signal (CSI-RS) – in particular, on non-zero-power CSI-RS (NZP CSI-RSs) or on CSI interference measurements (CSI-IM) resources, respectively. The results shown in this study indicate that interference measurements based on NZP CSI-RS resources outperform the interference measurements from CSI-IM resources for the new feedback reporting types. In addition, the obtained results show that an indication of the estimated BLEP of a PDSCH transmission allows faster convergence compared to legacy OLLA to achieve the predefined target BLER. These are important findings to fulfil the tight latency requirements in practical URLLC deployments of 5G NR networks.

The rest of the paper is organized as follows: Section II describes the CSI feedback framework, introducing the ILLA and OLLA schemes. In Section III, the two new feedback reporting types based on PDSCH decoding performance are described. In Section IV, the system model and interference measurement methodologies are presented. Then, in Section V, the performance evaluations, the related performance metrics and the actual numerical results are described and analysed. Finally, in Section VI, the conclusions of this study are drawn.

## II. Channel state information feedback

The CSI feedback from the UE plays a key role in URLLC as it guides the gNB to perform correct scheduling and link adaptation decisions. In this case, the UE selects the most optimal parameters for DL transmission based on a number of measurements performed on CSI-RS signals. Such parameters include CQI, rank indicator (RI) and precoder-matrix indicator (PMI) which are reported by the UE and used at the gNB side to adjust the upcoming transmissions parameterization. The CSI-RS is a UE specific signal used to derive the radio channel quality and to perform interference measurements, while the demodulation reference signal (DM-RS) refers to the known training signals and it is used for channel estimation [10]. In our evaluation framework, CSI-RS spans over the whole system bandwidth and different interference measurement methodologies can be used to tackle the inter-cell interference in 5G NR according to the pilots configuration. On one hand, the NZP CSI-RS resources are normally used to perform channel measurements but can be used to perform interference measurements by subtracting the estimated serving cell reference signal from the overall received signal. On the other hand, CSI-IM resources containing zero power resources can be used to directly measure the interference from neighbouring cells. These two methods are further discussed in Section IV.

### A. Link Adaptation

The purpose of the link adaptation is to enable a reliable data rate and throughput in the radio link adapting the transmission parameters at gNB side [11]. LA schemes consists mainly on the so-called inner loop link adaptation (ILLA) and outer loop link adaptation (OLLA). The ILLA scheme is used to determine the transmission parameters and resources by adapting the MCS in future transmissions based on the CQI feedback reports by the UE. Based on these CQI reports, the gNB can select the proper transmission power level, MCS and allocated resources for the varying channel response in time and frequency domains. The CQI is associated with a MCS index according to the current SNR measurements by the UE to accurately estimate the spectral efficiency (code rate and modulation order), providing an accurate estimate of the current channel conditions in the radio link. The exact CQI indices and their interpretations are given in [12]. The

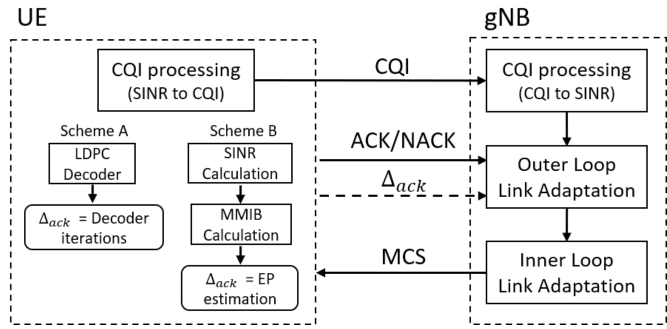



Fig. 1: Inner Loop Link Adaptation (ILLA) and Outer Loop Link Adaptation (OLLA) block diagram including the new feedback reporting ($\Delta_{\text{ack}}$) based on PDSCH decoding performance.

CQI report provides an estimate of the MCS to be used in the radio link so that a predefined $\text{BLER}_{\text{Target}}$ can be guaranteed for the given channel conditions. In particular, the higher (or lower) the CQI index, the higher (or lower) the MCS is defined. Besides, the CQI reporting granularity can be wideband or sub-band CQI. The former implies that the UE feedback report corresponds to only one wideband CQI value for the transmission bandwidth, while the latter implies that the UE feedback report corresponds to one CQI for each subband. In addition, the CQI frequency can be periodic, aperiodic or semi-persistent. In this paper we focus on a periodic wideband CQI to reduce the uplink overhead, where the CQI is reported with a periodicity of 5 slots.

### B. Outer Loop Link Adaptation based on ACK/NACK feedback

Relying on a fixed mapping between received CQI reports and estimated MCS may result in CQI inaccuracies due to the inherent channel conditions variations and CQI measurement and reporting delays. Therefore, an OLLA scheme is commonly used to cope with CQI inaccuracies by adjusting the SINR values derived from reported CQI with an estimated offset ($\Delta_{\text{OLLA}}$) before mapping it to an MCS index. This is expressed as follows:

$$\text{SINR}(f,k) = \text{SINR}(f,k) - \Delta_{\text{OLLA}} \tag{1}$$

for the set of received reference subcarriers indeces $f$ and OFDM symbol indeces $k$. Based on the HARQ feedback, the offset $\Delta_{\text{OLLA}}$ is continuously adapted aiming to converge to a pre-defined $\text{BLER}_{\text{Target}}$. The offset is either increased or decreased by a fixed step up and step down value ($\Delta_{\text{up}}$, $\Delta_{\text{down}}$), which correspond to a positive or negative acknowledgement signal reception (ACK and NACK), respectively. This process is illustrated in the left hand side of Fig. 2. The ratio between the predefined step values determines the $\text{BLER}_{\text{Target}}$ as follows:

$$\text{BLER}_{\text{Target}} = \frac{1}{1 + \frac{\Delta_{\text{up}}}{\Delta_{\text{down}}}} \tag{2}$$

For example, to achieve a BLER target of 10% (as commonly assumed and utilized for eMBB services), a typical configuration consists on setting $\Delta_{\text{up}} = 1$ dB and $\Delta_{\text{down}} = 0.1$ dB. For lower BLER targets as required for URLLC, this OLLA method does not scale well as the resulting $\Delta_{\text{down}}$ value

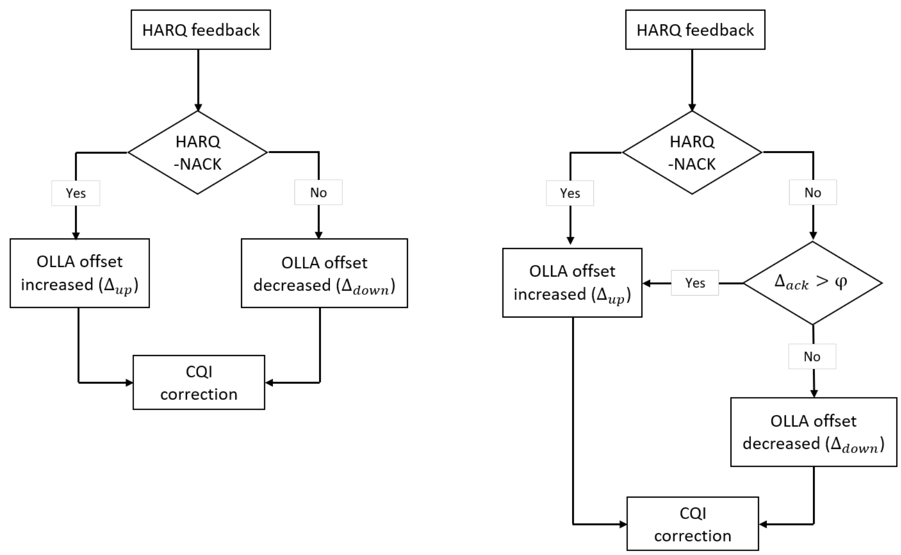



Fig. 2: Detailed block diagrams for legacy OLLA scheme based on ACK/NACK feedback (left), and new OLLA feedback reporting ($\Delta_{\text{ack}}$) based on PDSCH decoding (right) for a threshold $\varphi$ corresponding to the number of decoder iterations (Scheme A) or estimated block error probability (Scheme B).

is very small (e.g. $\Delta_{\text{down}} = 0.000005$ to achieve $\text{BLER}_{\text{Target}} = 10^{-5}$) which may lead to long convergence times of days or even weeks. This motivates new reporting schemes which can guarantee OLLA convergence within reasonable time.

## III. Outer Loop Link Adaptation based on New Soft-ACK Decoding Feedback Methods

In order to support OLLA operation in URLLC scenarios, the offset $\Delta_{\text{OLLA}}$ should be updated not only based on a binary HARQ NACK/ACK feedback where the amount of NACKs events will be negligible, but based on additional soft information which is available already before an error happens in the DL transmission. Overall, the adjustment of the offset $\Delta_{\text{OLLA}}$ should be triggered also by ACKs reception based on the decoding performance. This could be performed in a form of soft-ACK scheme which allows faster convergence of OLLA scheme to fulfill the latency requirements in URLLC. Based on 3GPP agreements [13], the new feedback reporting could be determined by the UE based on experienced SINR or LLRs, number of LDPC decoder iterations or estimated BLEP. In this paper, we formulate and analyse two possible new reporting schemes based on PDSCH decoding which are described and summarized below.

### A. *Soft-ACK based on Decoding Margin (Scheme A)*

The so-called Scheme A is based on an indication of the decoding margin of a PDSCH transmission, in particular, whether the decoded PDSCH pass or fail with high or low margin based on the number of LDPC iterations required for successful decoding of the data. Similar idea has been noted conceptually also in [14]. Therefore, OLLA scheme could be adjusted based on the decoding margin in addition to NACK. In this study, the received vector is processed by a min-sum LDPC decoder algorithm [15], where the decoder stops if the estimated vector has been successfully decoded and corresponds to the codeword or in case a maximum number of iterations has been reached. The number of the decoder iterations required for successful decoding are stored and used to trigger OLLA in a form of soft-ACK feedback report ($\Delta_{\text{ack}}$). It should be noted that the exact decoder algorithm may differ per implementation, and therefore, the decoding margin to adjust OLLA should be defined accordingly in an empirical manner as the final performance will depend on where the threshold is set. In this study, a thresholds $\varphi$ of 3 iterations has been chosen while the maximum number of iterations is set to 15. This process is illustrated in the left hand side of Fig. 1 on top of the legacy OLLA scheme framework.

### B. *Soft-ACK based on Estimated BLEP (Scheme B)*

The so-called Scheme B, discussed initially in [16], is based on an indication of the estimated block error probability (BLEP) of a PDSCH transmission. The processing approach for deriving the BLEP is to calculate the mutual information per transmitted bit (MIB) on all resource elements (REs) of the current transmitted data [17]. This is derived from the post-combined SINR samples from the decoder input in the form of a look-up-table (LUT) based on pre-stored link-level simulations, i.e $\text{MIB} = \text{LUT}(\text{SINR})$. The mean mutual information (MMIB) for the transport block is calculated by means of averaging over all REs. Finally, the BLEP estimate is calculated taking into account the code rate and transport block size values as a function $\text{BLEP} = \text{LUT}(\text{MMIB}, \text{TBS}, \text{R})$ and the BLEP is reported back to the gNB in a form of soft-ACK feedback report ($\Delta_{\text{ack}}$) by the UE. In this study, several thresholds ($\varphi$) have been evaluated for comparison purposes corresponding to the defined $\text{BLER}_{\text{Target}}$ of 0.1% and 1%. This process is also illustrated in the left hand side of Fig. 1 on top of the legacy OLLA scheme framework.

These new reporting schemes allow to adjust OLLA offset continuously following each transport block transmission and therefore, the channel variations in URLLC scenarios can be tracked accurately and the convergence time reduced. In this work, it is assumed that the soft-ACK feedback information is immediately reported to the gNB after each DL transport block reception. Nevertheless, it is also possible to do averaging of several $\Delta_{\text{ack}}$ values to reduce the uplink reporting overhead.

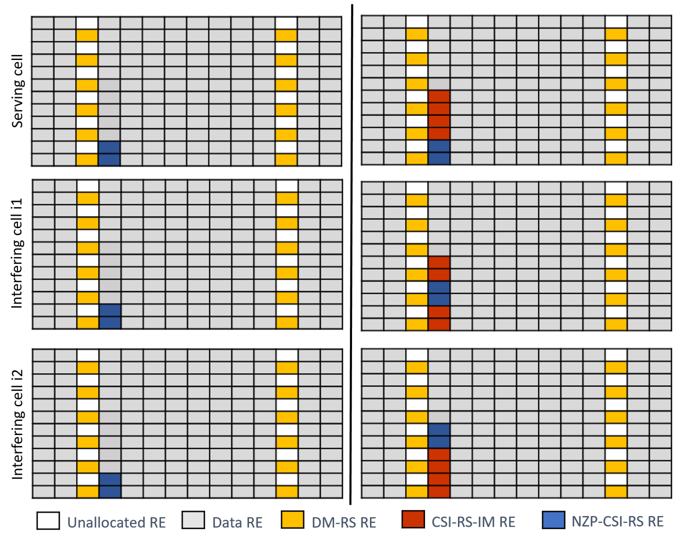



Fig. 3: Illustration of the resource block allocation structure for interference measurement approach $\mathrm{IM}_1$ based on NZP CSI-RS (left) and interference measurement approach $\mathrm{IM}_2$ based on CSI-IM (right).

A pictorial representation of this process is illustrated in Fig. 2. For legacy OLLA operation (left hand side of Fig. 2), the offset $\Delta_{\text{OLLA}}$ is decreased by $\Delta_{\text{down}}$ upon ACK reception and, increased by $\Delta_{\text{up}}$ upon reception of NACK. In case one of the new feedback reporting types is enabled (right hand side of Fig. 2), the same principles for legacy OLLA hold but the offset $\Delta_{\text{OLLA}}$ is increased by $\Delta_{\text{up}}$ upon ACK reception if the reported feedback $\Delta_{\text{ack}}$ is above the defined threshold $\varphi$, where $\Delta_{\text{ack}}$ corresponds to the number of decoder iterations (Scheme A) or estimated block error probability (Scheme B). In addition, the step sizes $\Delta_{\text{up}}$ and $\Delta_{\text{down}}$ should be properly defined to guarantee OLLA convergence. Due to the fact that $\Delta_{\text{down}}$ will result in very small values according to Eq. 2 definition for the typical URLLC scenarios, the step size has been manually defined for each $\mathrm{BLER}_{\mathrm{Target}}$ to 0.03 and 0.003 for $\mathrm{BLER}_{\mathrm{Target}}$ of 1% and 0.01%, respectively.

## IV. System Model and Interference Measurement Methods

The system model consists of one serving cell and two interfering cells assuming a cell-edge user suffering from strong inter-cell interference. The interference from each cell is scaled based on the interference model and added to the overall signal using predefined set of dominant interferer proportion (DIP) ratios in order to assess the link level performance with interference cancellation receivers. The interference profiles were developed in 3GPP in terms of the number of interfering gNBs to consider, where the DIP profile defines the ratio of the power of a given interfering base station over the total overall interference-plus-noise power. Subsequently, profiles conditioned on geometry were defined in [18], and predefined interference-to-noise-ratio (INR) profiles defined. In this study, INR3 profile is used, which corresponds to one strong and one weak interferer with a DIP profile equal to 1.73 dB and -8.66 dB, respectively. Therefore, the received signal is defined as follows, expressed here for an arbitrary active subcarrier and OFDM symbol:

$$\mathbf{y} = \mathbf{H}_s\mathbf{x}_s + \mathbf{H}_{i_1}\mathbf{x}_{i_1} + \mathbf{H}_{i_2}\mathbf{x}_{i_2} + \mathbf{n} \tag{3}$$

TABLE I: Considered 5G NR physical layer parameterization

| Parameter | Value | | |
|---|---|---|---|
| Carrier frequency | 4 GHz | | |
| Sub-carrier spacing | 15 kHz | | |
| Channel Bandwidth | 20 MHz | | |
| Allocation size | 100 | | |
| OFDM symbols | 14 | | |
| Channel model | TDL-A DS = 30ns | | |
| Antenna configuration | 2 Tx × 2 Rx | | |
| Waveform | CP-OFDM | | |
| UE velocity | 3 km/h | | |
| DMRS configuration | Type A, 2 symbols per slot | | |
| CQI reporting | Periodic wideband CQI every 5 slots | | |
| Channel estimation | Realistic | | |
| Receiver algorithm | MMSE-IRC | | |
| DIP profiles | [-1.73, -8.66] dB | | |
| OLLA schemes | Legacy | Scheme A | Scheme B |
| $\mathrm{BLER}_{\mathrm{Target}}$ | $[0.1, 1]\%$ | $[0.1, 1]\%$ | $[0.1, 1]\%$ |
| $\Delta_{up}$ (dB) | 1 | 1 | 1 |
| $\Delta_{down}$ (dB) | [0.00051,0.0051] | [0.003, 0.03] | [0.003, 0.03] |
| Threshold ($\varphi$) | - | 3 | $[0.1, 1]\%$ |

where $\mathbf{H}_s$, $\mathbf{H}_{i_1}$ and $\mathbf{H}_{i_2}$ are the channel response matrices of the serving and interfering cells, respectively, $\mathbf{x}_s$, $\mathbf{x}_{i_1}$, $\mathbf{x}_{i_2}$ are the transmitted symbol vectors of the serving and interfering cells, respectively, and $\mathbf{n}$ is the the noise vector.

In this study, an interference-aware receiver is assumed as baseline to suppress the inter-cell interference. In particular, a minimum mean square error - interference rejection combining (MMSE-IRC) receiver. In this case, the interference-plus-noise covariance matrix of the received signal should be properly estimated, as the more accurate the estimate of the covariance matrix the better the MMSE-IRC receiver will perform. Defining $\mathbf{r}$ as the total interference plus noise vector, the interference covariance matrix of the received signal $\mathbf{y}$ fed to the MMSE-IRC receiver for demodulation can be defined as:

$$\mathbf{C}_y = E[\mathbf{y}\mathbf{y}^H] = \sigma_s^2\mathbf{H_s}\mathbf{H_s}^H + \mathbf{R}_r \tag{4}$$

where $(\cdot)^H$ corresponds to the conjugate-transpose and $\sigma_s^2$ is the power of the useful signal. Consequently, the interference plus noise covariance estimate is defined as:

$$\hat{\mathbf{R}}_r = \hat{\mathbf{r}}_{\mathbf{IM}_j}\hat{\mathbf{r}}_{\mathbf{IM}_j}^H \tag{5}$$

where $j$ refers to the interference measurement methodology.

Based on [19], the best overall performance was achieved by measuring non-precoded interference for a fixed BLER target of 10%. Therefore, in this study we focus on non-precoded interference, comparing both interference measurement methodologies for the new OLLA schemes proposed for URLLC scenarios. In a first interference measurement approach ($\mathrm{IM}_1$), NZP CSI-RS resources are scheduled in the serving cell and collide with NZP CSI-RS resources from the interfering cells. The NZP CSI-RS resources can be used to perform interference measurements relying on the knowledge obtained from the serving cell reference signal and subtracting it from the overall received signal. The raw interference plus noise sample measurement is now defined as:

$$\hat{\mathbf{r}}_{\mathbf{IM}_1} = \mathbf{y} - \hat{\mathbf{H}}_s\mathbf{x}_s \tag{6}$$

where $\hat{\mathbf{H}}_s$ is the estimated channel response matrix of the serving cell based on the NZP CSI-RS pilots. The corresponding covariance estimate is obtained then as in (5).

In the second interference measurement approach ($\mathrm{IM}_2$), NZP CSI-RS is used for channel measurements while the interference measurements rely on CSI-IM resources. Therefore, NZP CSI-RS from the serving cell overlaps with CSI-IM resources from interfering cells and the interference from other cells can be directly measured in CSI-IM resources from the serving cell. The raw interference plus noise sample measurement is thus now defined as:

$$\mathbf{r}_{\mathrm{IM}_2} = \mathbf{H}_{i_1}\mathbf{x}_{i_1} + \mathbf{H}_{i_2}\mathbf{x}_{i_2} + \mathbf{n} \quad (7)$$

while again the actual covariance estimate is obtained as in (5).

The exact configuration of the defined interference measurement approaches are shown in Fig 3. The $\mathrm{IM}_1$ method based on NZP CSI-RS is illustrated in the top part of Fig 3, where CSI-RS resources are allocated to the OFDM symbol following the first DMRS symbol and it occupies two subcarriers in frequency domain. The resources from different gNBs are overlapping and the total interference can be measured as defined in (6). The $\mathrm{IM}_2$ method based on CSI-IM is illustrated in the bottom part of Fig 3, where CSI-IM resources overlap with NZP CSI-RS resources from other gNBs and are reserved in all gNBs to perform interference measurements. The total interference can be measured as defined in (7).

## V. Performance Analysis and Comparisons

In this section, performance evaluations are provided focusing on the throughput and BLER performance of the new feedback reporting types, proposed for URLLC scenarios, while also comparing with the legacy OLLA scheme. Besides, the convergence speeds achieved by these OLLA schemes are analysed and compared. All evaluations are performed using a 3GPP standardization compliant 5G NR radio link simulator based on the assumptions described in the Release 17 work item [9]. Table I summarizes the exact link level simulation assumptions used in the upcoming evaluations.

### *A. Performance of OLLA Schemes*

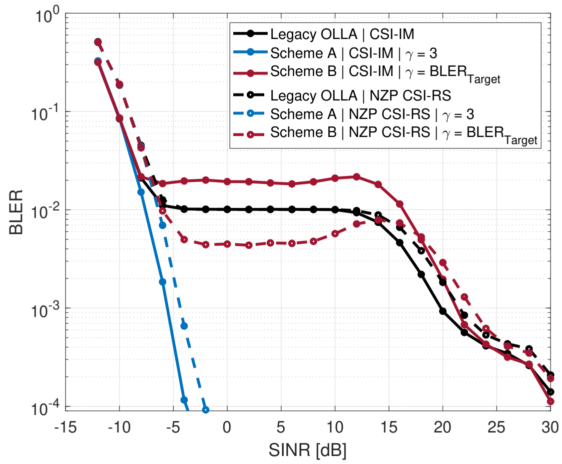
The aim of the two new feedback reporting types for URLLC scenarios analysed in this study is to help the gNB to adjust OLLA more frequently and ensure fast convergence through the soft-ACK feedback in addition to classical NACKs. Therefore, the legacy OLLA framework is modified and the offset $\Delta_{\mathrm{OLLA}}$ is adjusted towards more conservative MCS selection before leading to a decoding error in case the observed $\Delta_{\mathrm{ack}}$ is higher than the predefined threshold. The performance results of these schemes based on PDSCH decoding are shown in Fig. 4 in terms of throughput and BLER, while being also compared to the legacy OLLA scheme for two $\mathrm{BLER}_{\mathrm{Target}}$ values of 1% and 0.1%. These values are chosen smaller than the common values used in eMBB scenarios, i.e 10%, while assuring convergence in the simulations.

For Scheme A, lower BLER performance can be achieved compared to legacy OLLA since the OLLA scheme is adjusted towards more robust MCSs based on the decoder performance feedback. However, as it can be observed in Fig. 4 (a) and (b), this scheme does not clearly converge to any $\mathrm{BLER}_{\mathrm{Target}}$. Therefore, in terms of throughput, Fig. 4 (c) and (d) show that Scheme A results in degraded performance compared to the legacy OLLA scheme. A lower threshold $\Delta_{\mathrm{ack}}$ for Scheme A is expected to lead to a lower BLER performance together with a reduced throughput. Therefore, the threshold $\Delta_{\mathrm{ack}}$ for this scheme could be increased to improve the final throughput performance. However, it seems not feasible to achieve the desired $\mathrm{BLER}_{\mathrm{Target}}$ with this approach regardless of the defined threshold. In addition, it should be noted that this scheme steers OLLA based on the number of LDPC iterations required for successful decoding of the data. Hence, different LDPC decoders could highly differ in terms of convergence and the threshold should be defined empirically per use case and terminal implementation.

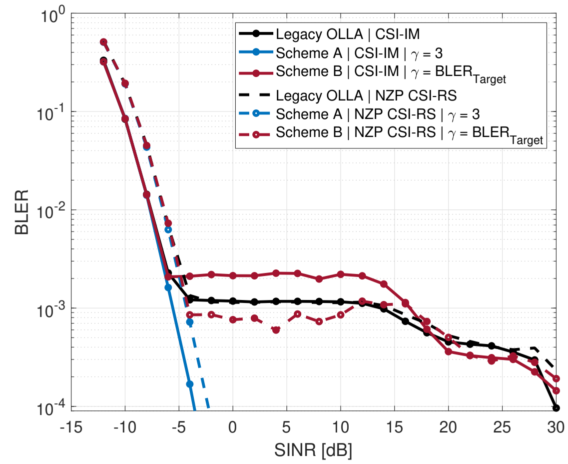
For Scheme B, the predefined $\mathrm{BLER}_{\mathrm{Target}}$ can be achieved and similar performance is observed compared to legacy OLLA in terms of throughput. In this case, the step sizes $\Delta_{\mathrm{up}}$ and $\Delta_{\mathrm{down}}$ should be properly defined to guarantee OLLA convergence for the defined $\mathrm{BLER}_{\mathrm{Target}}$ per transmitted transport block. Due to the fact that $\Delta_{\mathrm{down}}$ will result in very small values according to legacy OLLA definition, the step size is redefined for each $\mathrm{BLER}_{\mathrm{Target}}$ in this study to guarantee convergence of OLLA scheme together with a new steering method based on an indication of the estimated BLEP for the current transmission. It can be observed that in this case the average BLER performance is closer to the target while the final performance achieved by this scheme will also depend on the exact interference measurement methodology. This approach benefits from an explicit indication of the BLEP observed by the UE and can provide a good approximation to cope with CQI innacuracies together with faster convergence times in real URLLC scenarios. Based on these results, we focus on Scheme B in the rest of the paper, to analyse the impact of the different interference measurement methodologies and the corresponding achievable convergence times.

### *B. Performance of Interference Measurement Methods*

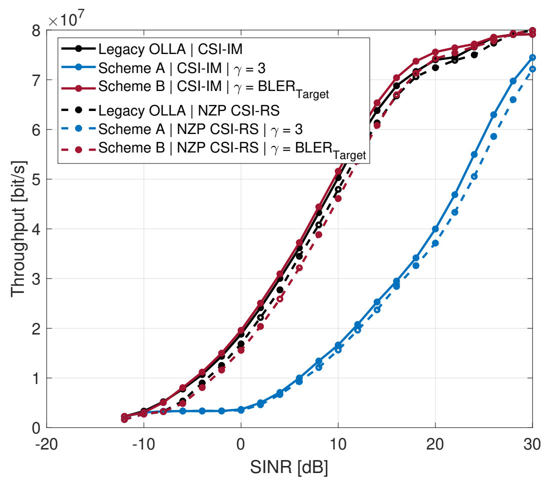
The two interference measurements approaches based on NZP CSI-RS ($\mathrm{IM}_1$) and CSI-IM resources ($\mathrm{IM}_2$) are next analyzed further, based on the results in Fig. 4, while also comparing different OLLA schemes. As highlighted earlier in the paper, the more accurate the estimate of the covariance matrix, the better the MMSE-IRC receiver will perform. Based on evaluations shown in Fig. 4, similar BLER and throughput performance can be achieved between $\mathrm{IM}_1$ and $\mathrm{IM}_2$ for the legacy OLLA scheme. Therefore, both IM methods provide good performance to be used in 5G NR networks. Focusing then on the new feedback reporting type proposed for the so-called scheme B, $\mathrm{IM}_1$ based on NZP CSI-RS resources provides the best BLER performance with reduced resource allocation overhead. Specifically, the interference measured by this $\mathrm{IM}_1$ method is higher and it results in a conservative MCS selection based on the feedback reported by the UE. On the other hand, the interference measured by the $\mathrm{IM}_2$ method seems to be lower and it leads to an aggressive MCS selection. In addition, $\mathrm{IM}_2$ method somewhat exceeds the $\mathrm{IM}_1$ method in terms of throughput performance for the two new reporting schemes. Based on these results, different IM methods yield different levels of measured interference and play an important role in the OLLA schemes' final performance. Therefore, we focus on the $\mathrm{IM}_1$ method in the next section, to further analyse the convergence speed of the proposed reporting Scheme B while also comparing to legacy OLLA.



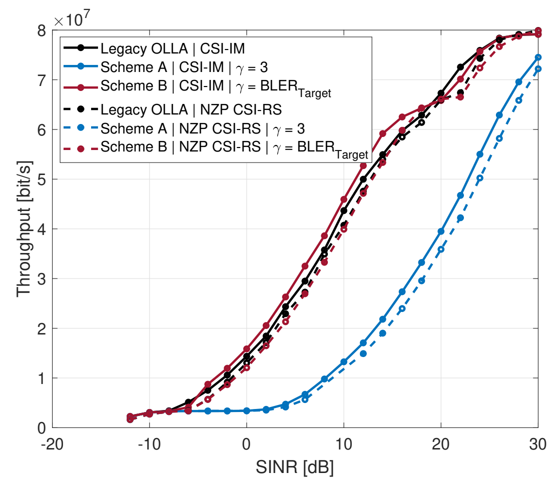

(a) BLER performance. $\mathrm{BLER_{Target}} = 1\%$




(b) BLER performance. $\mathrm{BLER_{Target}} = 0.1\%$




(c) TP performance. $\mathrm{BLER_{Target}} = 1\%$




(d) TP performance. $\mathrm{BLER_{Target}} = 0.1\%$

Fig. 4: 5G NR BLER and Throughput performance comparison for different OLLA schemes and interference measurement approaches ($\mathrm{IM}_1$ based on NZP CSI-RSs and $\mathrm{IM}_2$ based on CSI-IM). The performance of the legacy HARQ-ACK/NACK OLLA is shown in black while those of the two new reporting schemes based on PDSCH decoding performance are shown in blue (Scheme A, building on an indication of the number of LDPC iterations of a PDSCH transmission) and in red (Scheme B, building on an indication of the estimated block error probability of a PDSCH transmission), respectively.

### *C. OLLA Convergence Performance*

A new reporting scheme based on PDSCH decoding information allows OLLA to converge faster based on successful transmissions, enabling steering OLLA adjustment before leading to a NACK. In this context, the distribution of the events leading to an increase of the offset $\Delta_{\mathrm{OLLA}}$ towards more robust MCSs is illustrated in the top part of Fig. 5. In the case of legacy OLLA scheme, these events correspond to the NACK occurrences while for scheme B, they correspond to the NACK occurrences together with ACK reception when the reported feedback $\Delta_{\mathrm{ack}}$ is above the defined threshold. It can be observed that for the latter, the events leading to a $\Delta_{\mathrm{up}}$ are almost uniformly distributed within the simulation time while for legacy OLLA they are more scattered leading to slower convergence times. For example, the percentage of events leading to a $\Delta_{\mathrm{up}}$ within the first 1% simulation time is approximately 3.7% and 1.1% for legacy OLLA and Scheme B, respectively. This implies that the experienced BLER is higher for legacy OLLA and longer times are required to reach the target compared to the proposed Scheme B, as it can be also observed in the bottom part of Fig. 5. In particular, we have analysed that the average time between events leading to a $\Delta_{\mathrm{up}}$ adjustment is 27% and 25% slower (for $\mathrm{BLER_{Target}}$ of 1% and 0.1%, respectively) in the case of legacy OLLA compared to scheme B, for the SNR range where the BLER performance remains constant. Based on these findings, it is concluded that the new reporting scheme B proposed in this study allows faster convergence compared to legacy OLLA scheme.

As a future research topic, there are additional means to improve OLLA convergence speed in URLLC, such as using a conditional OLLA scheme based on mean BLEP estimation, as initially suggested in [20]. When the last BLEP sample meets the BLER target but recent mean BLEP exceeds it, such conditioning can prevent OLLA adjustments towards more aggressive MCS selection. Conditioning also allows one to optimize $\Delta_{\mathrm{up}}$ and $\Delta_{\mathrm{down}}$ more freely and flexibly, so that they do not depend on BLER target according to Equation (2). Both

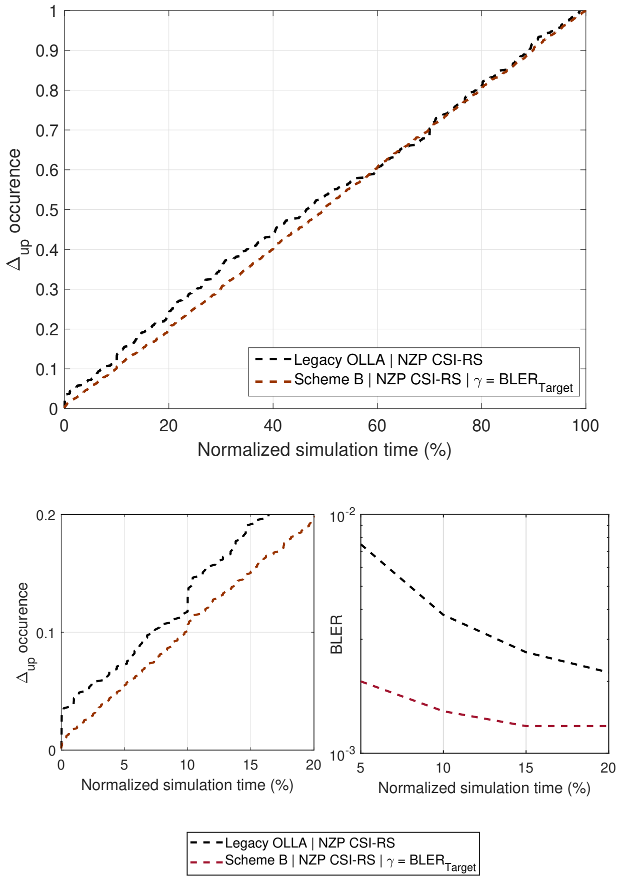



Fig. 5: Convergence of the normalized cumulative sum of the events leading to $\Delta_{\mathrm{up}}$ for legacy HARQ-ACK/NACK OLLA scheme and the so-called Scheme B based on indication of the estimated block error probability of a PDSCH transmission for a SNR of 6 dB during the simulation time (top). Additionally, a closed look on the beginning of the simulation time together with the estimated BLER for a $\mathrm{BLER}_{\mathrm{Target}} = 0.1\%$ are provided (bottom).

mechanisms can be utilized when faster OLLA convergence is needed. These are important findings to be considered in real URLLC deployments together with the proper fine-tuning of the OLLA scheme parameterization.

## VI. Conclusions

In this paper, two new HARQ feedback reporting types beyond legacy NACK/ACK feedback approach, in the form of novel soft-ACK reports, were described and analysed, with specific emphasis on OLLA performance enhancement in URLLC scenarios. Stemming from the fact that the amount of legacy NACK events will be very rare in URLLC use cases, the new schemes are based on an indication of the number of LDPC iterations for successful decoding of the data (the so-called Scheme A), or alternatively, on an indication of the estimated BLEP of a PDSCH transmission (the so-called Scheme B). In addition, two interference measurement approaches were considered, analysed and compared based on NZP CSI-RS and CSI-IM resources, with the method based on NZP CSI-RS resources shown to provide the best overall performance for the new feedback reporting types. The obtained performance results also show that the Scheme A does not converge to any predefined target in terms of BLER performance while the Scheme B allows for well-behaving and substantially faster convergence times towards the predefined target when compared to the legacy OLLA approach. Therefore, this feedback reporting scheme is likely to be one important technical ingredient to achieve the tight requirements in future 5G NR URLLC services, with specific emphasis on industrial use cases, allowing for fast convergence times together with efficient radio link performance.

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