Channel Quality Feedback Enhancements for Accurate URLLC Link Adaptation in 5G Systems

Pocovi Gerardino, Guillermo Andres; Esswie, Ali Abdelmawgood Ali Ali; Pedersen, Klaus Ingemann

Published in:
2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)

DOI (link to publication from Publisher):
10.1109/VTC2020-Spring48590.2020.9128909

Publication date:
2020

Document Version
Accepted author manuscript, peer reviewed version

Channel Quality Feedback Enhancements for Accurate URLLC Link Adaptation in 5G Systems

Guillermo Pocovi[1], Ali A. Esswie[1,2], Klaus I. Pedersen[1,2]

[1]Nokia Bell Labs, Aalborg, Denmark
[2]Aalborg University, Aalborg, Denmark
E-mail: guillermo.pocovi@nokia-bell-labs.com

***Abstract*—Accurate downlink link adaptation is a major challenge for ultra-reliable and low-latency communications (URLLC) as a consequence of the random and unpredictable load variations at the interfering cells. To address this problem, this paper introduces enhancements to the channel quality indicator (CQI) measurement and reporting procedures for 5G New Radio (NR). The goal is to accurately estimate and report the lower percentiles of the user channel quality distribution. First, a simple and efficient technique is proposed for filtering the channel quality samples collected at the user equipment and, accordingly, estimating tail signal-to-interference-and-noise (SINR) performance. Second, a new CQI reporting format is introduced which better guides downlink scheduling and link adaptation decisions of small URLLC payloads at the gNB. The benefits of the proposed solutions are evaluated via advanced system-level simulations, where it is shown that the proposed solutions significantly outperform existing CQI measurement and reporting schemes. For instance, the 99.999% percentile of the experienced latency is reduced from 1.3 ms to 0.86 ms for the case when URLLC traffic is multiplexed with enhanced mobile broadband (eMBB) traffic.**

Index Terms— URLLC; 5G new radio; Channel quality indication (CQI); Link adaptation;

I. Introduction

The 5G New Radio (NR) standard provides enhanced support for enhanced mobile broadband (eMBB), and enables new vertical use cases which demand Ultra-Reliable Low-Latency Communications (URLLC) [1]. In this regard, the 3GPP Release-15 allows the transmission of 32-Byte payloads with a radio latency below 1 ms and 99.999% reliability; whereas the 3GPP community is currently finalizing Release-16 with further enhancements that increase the reliability bound to 99.9999% [2], and address new industrial use cases demanding even lower latencies down to 0.5 ms [3].

To fulfil the stringent URLLC requirements, 5G NR incorporates a wide range of enhancements as compared to preceding technologies. For instance, faster processing times and a flexible frame structure with shorter transmission time intervals (TTI) allow to fulfil the 1 ms latency requirement with up to one Hybrid Automatic Repeat Request (HARQ) retransmission within the latency budget [4]. This enables flexible link adaptation in the sense that a first transmission is scheduled to achieve a moderate block error probability (BLEP) target of, e.g., 10^{-3}, and rely on the HARQ process to ensure a residual BLEP below 10^{-5} for the retransmission [5].

In the downlink (DL) direction, link adaptation for the selection of a modulation and coding scheme (MCS) is based on the channel quality indicator (CQI) feedback information from the User Equipments (UE). For NR, the BLEP constraint associated with the CQI reports from the UEs is network-configured and can be either 10^{-1} or 10^{-5} [6]. The accuracy and integrity of the CQI reports are of vital importance for fulfilling the strict URLLC reliability requirements [5]. This is challenging in multi-cell cellular networks, where fast and random (unpredictable) interference fluctuations are often experienced, which make the signal to interference-and-noise ratio (SINR) at the UE to also vary rapidly [7], [8]. This problem is especially challenging under fractional-load conditions, as also observed for LTE [9]. In such cases, the MCS selection is typically assisted by adopting outer loop link adaptation (OLLA) mechanisms for fine-tuning the MCS selection at the gNB according to the received HARQ ACK/NACK feedback [10]. The open literature presents several studies on OLLA techniques and related enhancements, see e.g. [11] which proposes a self-optimization algorithm to adjust the OLLA initial offset, and [12] that introduces a dynamic OLLA step size adjustment. However, one of the main challenges of such techniques is their slow convergence time especially when operating with low BLEP targets ($\leq 10^{-3}$), thus, making them unsuitable for URLLC applications.

With the target of supporting even lower latency and/or higher reliability in upcoming NR releases, this paper proposes link adaptation enhancements for URLLC, including the UE reported CQI information. Examples of earlier pioneering studies on CQI design for orthogonal frequency division multiple access (OFDMA) systems to foster radio channel-aware scheduling and link adaptation include [13]–[18]. Common for those studies is that the objectives were to optimize the user experienced average data rate. However, for URLLC applications, the objective is to accurately control the BLEP for every single transport block transmission in coherence with the ultra-reliability constraint. Here, a CQI report is needed that corresponds to an estimate of the worst-case SINR conditions that the UE is likely to experience until the next received CQI [19]. In pursuit of such solutions, a simple and efficient technique is proposed for filtering the channel quality samples collected at the UEs to estimate tail of the UE-experienced SINR conditions. Secondly, a new CQI reporting format is introduced which better guides the scheduling and link adaptation decisions of small URLLC payloads at the gNB. The performance and benefits of the proposed techniques are evaluated in a highly-dynamic environment, including the effects of multiple users and cells and corresponding time-varying traffic and interference. Given the complexity of the system model, the adopted methodology consists of system-level simulations following the Release-16 NR modelling assumptions in 3GPP for URLLC [20].

The rest of the paper is structured as follows. Section II further sets the scene by introducing the system model and problem formulation, respectively. Section III provides an overview of the proposed CQI measuring and reporting procedures. Performance results are presented in Section IV, followed by conclusions in Section V.

II. Setting the Scene

A. Network Layout and Traffic Modeling

We consider a macro cellular network with C cells, deployed in a sectorized manner, each with three sectors and 500-meter inter-site distance. Two different traffic compositions are considered: (i), U_u URLLC UEs are deployed in each cell, where the URLLC traffic is modeled as small payloads of B_u Bytes, which arrive at each URLLC UE in the DL direction following a Poisson arrival process with a mean arrival rate λ [packets/s]. The offered load of URLLC traffic per cell is given by $U_u \times B_u \times \lambda$. In case (ii), additional U_e eMBB UEs are deployed in each cell, where the eMBB traffic is modelled with constant-bit-rate (CBR) DL flows, e.g. video streaming, consisting of a predefined number of packets n_e generated per UE, each with payload size of B_e and fixed inter-arrival time of T_e [s]. Once the n_e packets are successfully delivered to the UE, the UE leaves the network and a new one is generated at a random location in the network. The CBR load per cell is $U_e \times \frac{B_e}{(n_e-1)T_e}$.

Users are dynamically scheduled in both the time- and frequency domain using OFDMA. The physical layer configuration consists of 30 kHz sub-carrier spacing (SCS), a physical radio block (PRB) size of 12 sub-carriers (360 kHz), and a TTI duration of 2 OFDM symbols (71.4 μs). Considering the gNB and UE processing capabilities specified in [21], the adopted physical layer configuration allows to fulfil the 1 ms latency target even with one HARQ retransmission.

B. URLLC Link Adaptation Challenges

One challenge for accurate link adaptation (and scheduling) of URLLC payloads relates to the tracking of the radio channel and interference variations. Given that URLLC payloads are generally small-sized, they are often scheduled over less PRBs than available within the total carrier bandwidth, offering a weak frequency domain diversity for localized resource allocation, while some frequency diversity can be achieved with distributed resource allocation. In addition, the experienced UE SINR is highly time-variant due to rapid load fluctuations of the neighboring cells. As an example, Fig. 1 presents a time trace of the allocated PRBs of a cell serving a set of URLLC users (obtained from a dynamic system-level simulation). As can be observed from Fig. 1, the PRB activity is a highly time-variant random process, which causes the experienced SINR at different UEs to be rapidly time-variant as well (due to variations of the experienced inter-cell interference). This implies that if a UE measures the SINR on certain PRBs at a given time, it might be several dBs different shortly after (say from one TTI to another).

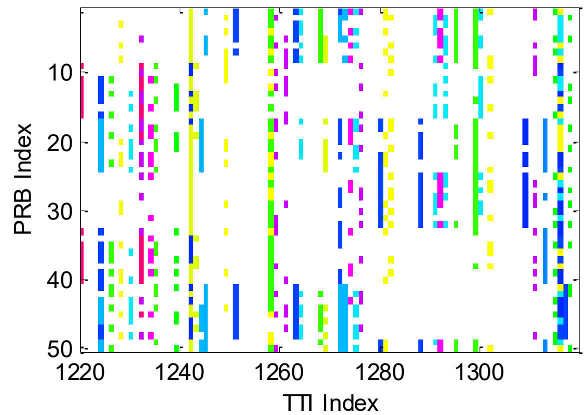

Fig. 1: Time trace of the downlink PRB allocation in one cell serving URLLC traffic. A color identifies one UE which is served in the downlink direction.

C. Objective of the Study

Due to UE SINR estimation imperfections, CQI measuring and reporting delays and the additional latencies such as gNB processing times, it is not considered realistic to accurately track the time- and frequency-variants of the UE experienced SINR. The objective is therefore to design a CQI report that expresses the worst-case SINR conditions that the UE is likely to experience until the next received CQI. One key challenge is to avoid a too-pessimistic CQI estimation, as it reduces the network spectral efficiency, and accordingly, limits the number of URLLC UEs that can be served in the network.

III. Proposed CQI Enhancements

In the following sub-sections, we describe the basic principles of the CQI measuring and reporting procedure as per the 5G NR standard, followed by the introduction of the two proposed CQI enhancements.

A. CQI Measuring and Reporting Procedure

The CQI represents the highest supported MCS with which the UE can decode its data with an error probability no larger than a certain constraint. The CQI takes into account the receiver type, number of antennas and potential interference cancellation/suppression capabilities at the UE. The CQI is included in the Channel State Information (CSI) feedback to the gNB, together with the preferred precoding matrix indicator (PMI), rank indicator (RI), among other UE reports [6, Sec. 5.2].

Fig. 2 shows a flow chart of the CQI measurement and reporting procedure. In the first step, the gNB configures the UE via the Radio Resource Control (RRC) signalling with one or multiple CSI reporting and resource settings. These include, among others, configuration of the time-domain behaviour of the report, e.g., aperiodic or periodic reporting, number of reported frequency sub-bands $\mathcal{S} = \{1, ..., S\}$, the CQI table which shall be used for the report, as well as the Channel State Information Reference Signals (CSI-RS) to be used for desired-signal and interference measurements.

Next, the UE performs channel quality measurements on the specified CSI-RS. Each individual measurement is filtered and used to estimate the UE's experienced SINR with the specified frequency resolution. The estimated SINR on each sub-band s is then mapped to the MCS index m from the specified CQI table that fulfils the following condition:

$$m_s^* = \arg\max_m \{R_{m,s} | P_e(\Gamma_s) \le P_{target}\} , \quad (1)$$

corresponding to the largest data rate $R_{m,s}$, that can be supported with a block error probability P_e not exceeding P_{target} if scheduled over the s-th sub-band (with experienced SINR Γ_s) using MCS index m. For NR, P_{target} can be either 10^{-1} or 10^{-5} and is implicitly derived from the configured CQI table. More details on the MCS entries for each CQI table can be found in [6]. In practice, this is achieved by having the UEs measure the experienced SINR, followed by evaluation of (1) given knowledge of the BLEP vs SINR mapping curve for each of the supported MCSs.

Finally, the UE formats the CQI report following the specified granularity. Two report formats are standardized: i) wideband CQI reports ($S = 1$), where the UE reports a single CQI index, and ii) frequency-selective CQI ($S > 1$), where the UE reports both a wideband CQI and the relative offset of each sub-band with respect to the wideband CQI value.

B. Biased Interference Filtering (BIF)

The first enhancement introduces time-domain filtering of channel quality samples collected at the UE. The UE performs desired-signal and interference measurements on CSI-RS as specified in the CSI resource configuration. As the interference represents one of the main sources of SINR variations, it is proposed that on each measurement instant n, the instantaneous interference measurement on the s-th sub-band, $x_s[n]$, is filtered with a low-pass first-order infinite impulse response (IIR) filter as follows:

$$y_s[n] = \begin{cases} \alpha_u \cdot x_s[n] + (1 - \alpha_u) \cdot y_s[n-1], & \text{if } x_s[n] \ge y_s[n-1], \\ \alpha_d \cdot x_s[n] + (1 - \alpha_d) \cdot y_s[n-1], & \text{if } x_s[n] < y_s[n-1], \end{cases} \quad (2)$$

where $x_s[n]$ and $y_s[n]$ are the instantaneous and filtered interference measurement on the sub-band s over the measurement interval n, and α_u and α_d determine the memory of the filter as well as its bias. As an example, Fig. 3 shows the filter's output for different settings of α_u and α_d, assuming a

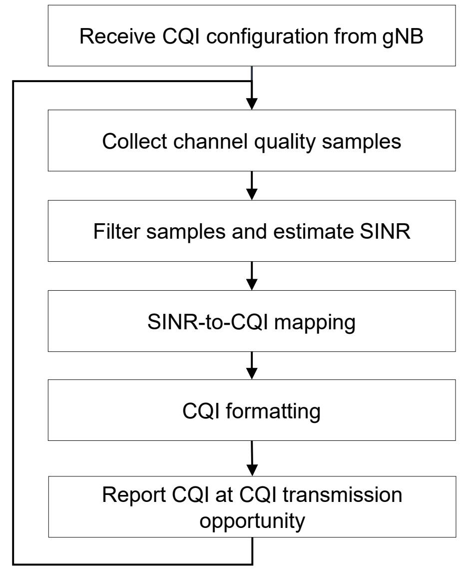

Fig. 2: CQI measurement and reporting operation at the UE.

zero-mean unit-variance Gaussian distribution at the filter's input. Settings with $\alpha_u = \alpha_d$ correspond to a standard exponentially-weighted moving average filter used for mean value estimation, whereas setting $\alpha_u > \alpha_d$ or $\alpha_u < \alpha_d$ allows to estimate lower or higher percentiles of the input distribution, respectively. Besides, for a fixed α_u/α_d ratio, the value of α_u determines the filter's memory, i.e. how much weight is given to the latest measurement as compared to the previous ones. The impact of α_u and α_d on the URLLC performance will be further examined in Section IV. Note that the presented filtering procedure is simple in the sense that it only requires storing one $y_s[n]$ sample per sub-band.

A frequency-selective CQI is reported to the gNB containing the filtered interference on each sub-band, $y_s[n]$, together with the latest desired-signal fading information. Note that the latter varies in a much slower time scale and can be generally tracked at the gNB for low UE speeds.

C. Worst-M CQI Report

Secondly, a new CQI format is proposed where the UE reports to the gNB: i) a wideband CQI value, that at maximum will result in a BLEP of P_{target} if the gNB schedules a payload with a MCS according to the recently received CQI over the entire band; and ii) a CQI value that at maximum will result in a BLEP of P_{target} if transmitting only over the worst-M subbands, without explicit indication on the position of those subbands.

The worst-M CQI allows the gNB to schedule a small URLLC payload randomly over the frequency-domain (either localized or spread allocation) while still guaranteeing high probability of successful decoding even if it experiences unfavourable conditions of fading and/or interference. Besides, the wideband CQI information can be used for allocations spanning over a larger bandwidth.

The proposed CQI reporting format is similar to the *Best-*

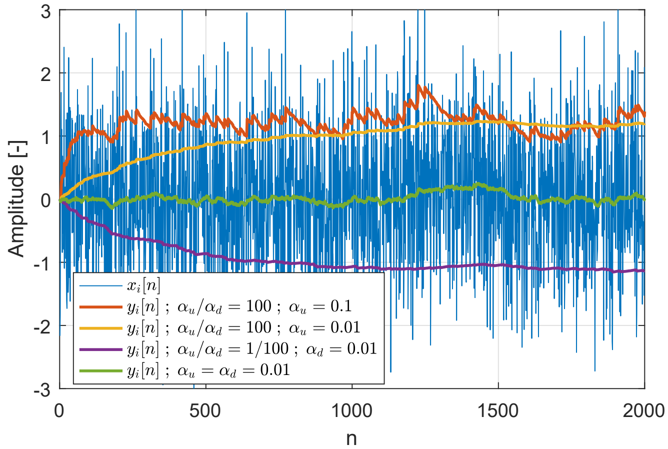

Fig. 3: Filter's input $x_s[n]$ and output $y_s[n]$ for different settings of α_u and α_d. $x_s[n]$ corresponds to a a zero-mean unit-variance Gaussian distribution.

M reporting standardized in LTE [1]; however, this scheme applies the opposite criterion when sorting the channel quality measurements, and does not include information on the positions of the M-worst subbands due to the limited benefit of frequency-selective information as observed from Fig. 1.

TABLE I: Simulation assumptions

Parameter	Value
Network env.	3GPP Urban Macro (UMa) network with 21 cells and 500 meter inter-site distance [22]
PHY numerology	30 kHz subcarrier spacing; 12 subcarriers per PRB; TTI size of 2 OFDM symbols (71.4 μs)
Carrier config.	20 MHz carrier bandwidth (50 PRBs) at 4 GHz
Duplexing	Frequency division duplexing (FDD)
Control channel	Error-free in-resource scheduling grants with dynamic link adaptation [7]
CQI/CSI configuration	CQI and PMI, reported every 1 ms with 1 ms processing delay; Sub-band size: 4 PRBs;
Antenna config.	4 x 4 single-user MIMO and MMSE-IRC receiver
Packet scheduler	Proportional Fair; strict priority for URLLC traffic
HARQ	Async. HARQ with Chase combining; Max. 6 HARQ retransmissions. Processing time as in [21]
RLC	RLC Unacknowledged mode
Traffic composition	Case a) 10 URLLC UEs per cell; Case b) 10 URLLC UEs + 10 eMBB UEs per cell
UE distribution	Uniformly distributed in outdoor locations
Traffic model	URLLC: FTP3 DL traffic; B_u = 50 B; Variable offered load per cell eMBB: CBR DL traffic: B_e = 160 kB; n_e = 10; 5 Mbps offered load per cell

IV. Performance Evaluation

A. Simulation Methodology

System-level simulations are used to evaluate the performance of the proposed CQI enhancements. The simulation assumptions are summarized in Table I. The network layout, UE distribution and traffic follow the description presented in Section II-A. The network is composed of $C = 21$ cells, with $U_u = 10$ URLLC UEs and optionally $U_e = 10$ eMBB UEs deployed in each cell.

The simulator's time resolution is one OFDM symbol, and it includes explicit modelling of the majority of radio resource management functionalities such as dynamic packet scheduling and HARQ, as well as time- and frequency-varying inter-cell interference. Closed-loop 4x4 single-user MIMO is assumed for each link and the UE receiver type is minimum mean square error with interference rejection combining (MMSE-IRC). URLLC users are scheduled with a single spatial stream, i.e. benefiting from both transmission and reception diversity against fast fading and radio channel fluctuations, whereas dynamic rank adaptation is assumed for eMBB users allowing multiplexing of up to two spatial streams for favourable SINR conditions.

A frequency- and QoS-aware packet scheduler is assumed, which prioritizes URLLC transmissions and HARQ retransmissions over first transmissions of eMBB traffic. Dynamic link adaptation is applied for both data and the in-resource control channel, which results in varying control overhead depending on the user signal quality and TTI duration (see [7]). The link adaptation is based on the periodical CQI report from the URLLC users. UEs are configured to periodically transmit a CQI report every 1 ms, and a 1 ms processing delay is assumed from the time the CQI is reported until it can be applied for downlink transmissions. Each sub-band consists of 4 PRBs, thus the UE reports CQI for $S = 13$ sub-bands. The proposed measurement and formatting enhancements in Section III are presented for different settings of α_u and α_d, and $M = 3$. The latter parameter has been selected in accordance with the average PRB allocation size of URLLC payloads. No outer-loop link adaptation methods are applied.

For each URLLC payload, the latency is measured from the moment it arrives at the serving cell until it is successfully received at the UE. This accounts for various constant and variable latency components, namely queuing delay, processing and frame alignment delay, and transmission delay; the latter includes the effects of HARQ retransmissions and payload segmentation over multiple TTIs. An *infinite* delay is assumed for payloads not successfully decoded after 6 HARQ retransmissions. The latency of each received URLLC payload is collected and used to form empirical complementary cumulative distribution functions (CCDF). The key performance indicator (KPI) is the achievable latency with 99.999% probability, i.e., the 10^{-5} percentile of the URLLC latency CCDF. The simulation time corresponds to at least 5.000.000 successfully received URLLC payloads in order to ensure a reasonable confidence level for the considered performance metric.

The obtained performance is compared against the following state-of-the-art schemes [7]: i) CQI based on latest/unfiltered channel quality measurements, which is a special case of the proposed BIF scheme with $\alpha_u = \alpha_d = 1$, and ii) CQI based on mean SINR estimation, which corresponds to $\alpha_u = \alpha_d < 1$.

B. Performance Results without eMBB Traffic

Fig. 4 shows the CCDF of the URLLC latency for different CQI schemes and fixed offered load of 10 Mbps per cell, for the case without eMBB traffic. URLLC transmissions experience a minimum delay of ~ 0.29 ms which is a consequence of the 71.4 μs transmission duration and encoding/decoding processing times at gNB and UE, respectively. At the 10^{-5} percentile, a CQI report based on instantaneous channel quality measurements ($\alpha_u = \alpha_d = 1$) is not sufficient to fulfil the 1 ms latency requirement. This is a consequence of the fast (per-TTI) varying load conditions which results in inaccurate link adaptation and thus a large number of HARQ retransmissions. In contrast, other configurations experience at most one HARQ retransmission at the 10^{-5} percentile, and thus achieve the 1 ms latency target accordingly. For instance, the BIF scheme achieves a retransmission probability between $2 \cdot 10^{-5}$ and $8 \cdot 10^{-6}$ with $\alpha_u/\alpha_d = 10$ and $\alpha_u/\alpha_d = 100$, respectively. That is, the latter parameter setting achieves the target 99.999% reliability with a single transmission, and hence, it can be considered an attractive CQI measurement solution for industrial use cases demanding latencies down to 0.5 ms.

Fig. 5 summarizes the latency at the 10^{-5} percentile for 8 Mbps and 14 Mbps offered loads of URLLC traffic. The benefits of the BIF scheme are mainly relevant for low offered URLLC loads since there are generally sufficient resources to operate with lower error-rate (lower MCS) without increasing the probability of queuing delay to other users. Worst-3 report also provides good URLLC outage performance, especially if the report is based on the time-averaged interference measurements ($\alpha_u = \alpha_d = 0.01$). At higher offered loads, the larger and fast-varying interference makes it difficult to achieve the required reliability with a single transmission, and therefore, both the proposed solution and the state-of-the-art scheme deliver a similar performance.

C. Performance Results with eMBB Traffic

Fig. 6 shows the URLLC performance for cases with a mixture of URLLC and eMBB users, with an offered load of 2 and 5 Mbps for URLLC and eMBB traffic, respectively. Even though URLLC transmissions are fully prioritized by the packet scheduler, the larger inter-cell interference from scheduling eMBB users significantly degrades the URLLC latency performance. For instance, the CQI scheme with $\alpha_u = \alpha_d = 0.01$, which was deemed suitable for the URLLC-only case (Fig. 4 and 5), does not longer fulfil the 1 ms latency target with 99.999% reliability when eMBB traffic co-exists in the system. This is a consequence of the significantly different interference pattern with frequent transitions between *low* load and *high* load (up to 100% PRB utilization) when eMBB users arrive or leave the system. In such conditions, there is a substantial benefit of using the proposed Worst-*M* and BIF technique, as these focus on estimating the tails of the UE's SINR distribution (worst-case interference conditions). The best performance is generally obtained with the BIF technique, whereas Worst-3 offers a slightly worse performance,

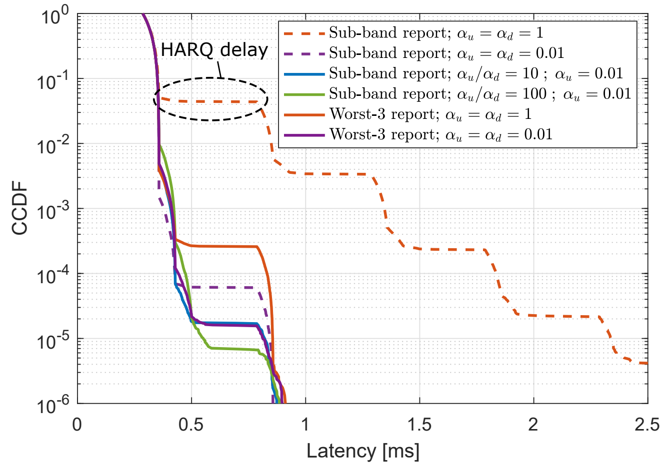

Fig. 4: URLLC latency distribution for different CQI reporting and measurement schemes. Offered load of URLLC traffic is 10 Mbps per cell.

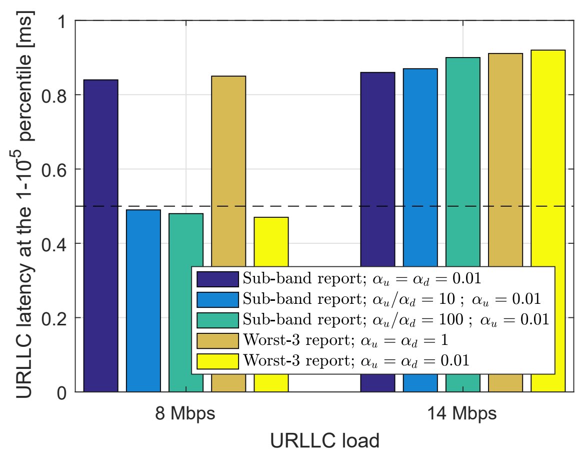

Fig. 5: Summary of URLLC latency performance at the 99.999% percentile for two offered loads of URLLC traffic. The 0.5 ms latency target in NR Release-16 is indicated with a vertical dashed line.

although, it has the benefit of lower UL signalling overhead due to single sub-band reporting.

V. Conclusions

In this paper we have addressed the problem of link adaptation imperfections for reliable downlink transmissions of URLLC traffic. Two enhancements have been proposed to the Channel Quality Indicator (CQI) measuring and reporting procedure at the UE: *Biased Interference filtering* (BIF) of the collected channel quality measurements, and *Worst-M* CQI reporting format, which target to estimate and report the lower percentiles of the UE's channel quality distribution. Performance results show how the proposed schemes facilitate downlink transmission of small and sporadic URLLC payloads with low BLEP constraints, e.g. $< 10^{-3}$, without relying on traditional outer-loop link adaptation methods. In scenarios with low offered loads of URLLC traffic, BIF and the Worst-M

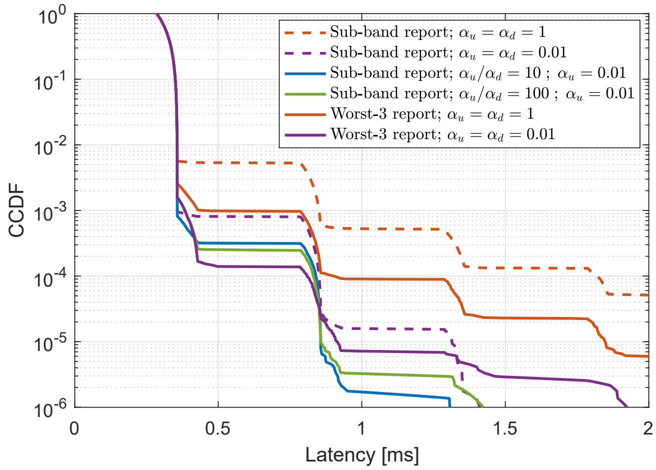

Fig. 6: URLLC latency distribution for different CQI reporting and measurement schemes in scenarios with a mixture of URLLC and eMBB traffic. The offered load is 2 and 5 Mbps for URLLC and eMBB traffic, respectively.

schemes allow to achieve latencies down to 0.5 ms at the 99.999% percentile, which is a new requirement imposed by some industrial vertical applications. In scenarios with a mixture of URLLC and dynamic eMBB traffic, the proposed solutions significantly outperform existing techniques and achieve the 1 ms and 99.999% URLLC requirement.

Acknowledgements

This work is partly funded by the Innovation Fund Denmark (IFD) under File No. 7039-00009B and 7038-00009B.

References

[1] 3GPP Technical Specification TS 38.300 v15.3.1, "NR and NG-RAN Overall Description; Stage 2," Oct. 2018.
[2] 3GPP RP-181477, "New SID on Physical Layer Enhancements for NR URLLC ," June 2018.
[3] 3GPP Technical Specification TS 22.104 v16.0.0, "Service requirements for cyber-physical control applications in vertical domains," Dec. 2018.
[4] G. Pocovi, H. Shariatmadari, G. Berardinelli, K. Pedersen, J. Steiner, and Z. Li, "Achieving ultra-Reliable low-Latency communications: challenges and envisioned system enhancements," *IEEE Network*, vol. 32, no. 2, pp. 8–15, March 2018.
[5] H. Shariatmadari, Z. Li, M. A. Uusitalo, S. Iraji, and R. Jäntti, "Link adaptation design for ultra-reliable communications", *in Proc. IEEE ICC*, Kuala Lumpur, 2016, pp. 1-5.
[6] 3GPP Technical Specification TS 38.214 v15.3.0, "Physical layer procedures for data", Sept. 2018.
[7] G. Pocovi, B. Soret, K. I. Pedersen, and P. Mogensen, "MAC layer enhancements for ultra-reliable low-latency communications in cellular networks", *in Proc. IEEE ICC* , Paris, 2017, pp. 1005-1010.
[8] 3GPP R1-1901555, "Baseline performance achievable with Rel-15 URLLC for factory automation", Mar. 2019.
[9] V. Fernández-López, K. I. Pedersen, and B. Soret, "Interference characterization and mitigation benefit analysis for LTE-A macro and small cell deployments", *EURASIP Journal on Wireless Communications and Networking*, vol. 2015, no.1, April 2015.
[10] K. I. Pedersen et al., "Frequency domain scheduling for OFDMA with limited and noisy channel feedback," *in Proc. IEEE VTC*, Baltimore, MD, 2007, pp. 1792-1796.
[11] A. Durán, M. Toril, F. Ruiz, and A. Mendo, "Self-optimization algorithm for outer loop link adaptation in LTE," *IEEE Commun. Lett.* , vol. 19, no. 11, pp. 2005–2008, Nov. 2015.
[12] F. Blanquez-Casado, G. Gomez, M. Aguayo-Torres, and J. Entrambasaguas, "eOLLA: an enhanced outer loop link adaptation for cellular networks," *EURASIP Journal on Wireless Communications and Networking*, vol. 2016, no. 20, Jan. 2016.
[13] R. Agarwal, V. R. Majjigi, Z. Han, R. Vannithamby, and J. M. Cioffi, "Low complexity resource allocation with opportunistic feedback over downlink OFDMA networks," IEEE J. Sel. Areas Commun., vol. 26, no. 8, pp. 1462-1472, Oct. 2008.
[14] T. S. Kang and H. M. Kim, "Opportunistic feedback assisted scheduling and resource allocation in OFDMA systems," in Proc. IEEE ICCS, Oct. 2006, pp. 1-5.
[15] S. Yoon, O. Somekh, O. Simeone, and Y. Bar-Ness, "A comparison of opportunistic transmission schemes with reduced channel information feedback in OFDMA downlink," in Proc. IEEE PIMRC, Sep. 2007.
[16] J. Leinonen, J. Hamalainen, and M. Juntti, "Performance analysis of downlink OFDMA frequency scheduling with limited feedback," in Proc. IEEE ICC, Jun. 2008, pp. 3318-3322.
[17] Y.-J. Choi and S. Bahk, "Selective channel feedback mechanism for wireless multichannel scheduling," in Proc. IEEE WoWMoM, 2006.
[18] J. Chen, R. A. Berry, and M. L. Honig, "Performance of limited feedback schemes for downlink with finite coherence time," in Proc. IEEE ISIT, Jun. 2007, pp. 2751-2755.
[19] M. Bennis, M. Debbah and H. Vincent Poor, "Ultrareliable and low-Latency wireless communication: tail, risk, and scale," *Proceedings of the IEEE*, vol. 106, no. 10, pp. 1834-1853, Oct. 2018.
[20] 3GPP TR 38.824 v16.0.0, "Study on physical layer enhancements for NR ultra-reliable and low latency case (URLLC)", Mar. 2019.
[21] 3GPP R1-1808449, "IMT-2020 self-evaluation: UP latency analysis for FDD and dynamic TDD with UE processing capability 2 (URLLC)", Aug. 2018.
[22] 3GPP Technical Report TR 38.901, "Study on channel model for frequencies from 0.5 to 100 GHz", Dec. 2017.