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System Level Analysis of eMBB and Grant-Free URLLC Multiplexing in Uplink

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***Abstract*—5th generation radio networks should efficiently support services with diverse requirements. For achieving better resource utilization, the sharing of the radio channel between the different services is an attractive solution. While the downlink multiplexing can be well accomplished with dynamic scheduling, efficient multiplexing of enhanced mobile broadband (eMBB) and ultra-reliable low-latency communications (URLLC) in uplink is still an open problem. In particular, we consider the case of URLLC using grant-free allocation for sporadic transmissions, multiplexed on shared resources with eMBB with high data volume. Since the moment in which a grant-free transmission occurs is not known, URLLC and eMBB transmissions overlay. Power control settings are then assessed as a way to manage the performance trade-off between the services. Due to the complexity of 5G NR, the evaluation is based on advanced system level simulations. Insights regarding the configuration of fractional power control settings upon the coexistence of the different services are presented.**

I. Introduction

The recent 5th generation (5G) new radio (NR) specifications include features for conveying traffic with different characteristics and requirements. One example is enhanced mobile broadband (eMBB) which focuses on high volume of data transmissions, demanding high spectral efficiency. Ultra-reliable low-latency communications (URLLC) target instead, to deliver intermittent small payloads with high success probability in a short time interval. A baseline target for URLLC is to enable transmissions over the air interface of 32 bytes payloads within $1\,\mathrm{ms}$ and a $1-10^{-5}$ reliability [1]. The initial support of each of these services is readily provided by the 3GPP Release-15 specification [2]. However, the multiplexing of uplink traffic with different reliability requirements has gained attention, given the need of supporting heterogeneous services while ensuring efficient use of the radio resources [3].

The efficient multiplexing of eMBB and URLLC in downlink can be achieved by dynamic scheduling, with the high priority URLLC transmissions puncturing the eMBB allocation [4]. In uplink, similar concept can be employed with preemption schemes, both for intra-UE (for the same UE) and for inter-UE (between different UEs) traffic multiplexing. With this, eMBB transmission is paused while URLLC is granted to transmit. While this solution is valid for dynamic scheduled transmissions, the same is not applicable when grant-free schemes are utilized. Grant-free transmissions, specified as configured grants in NR [5], is one of the main enablers of uplink URLLC with very stringent requirements. In that, the resource allocation, as well as other physical layer parameters, are pre-configured by radio resource control (RRC) signaling. Thus, the usual handshake process, of sending a scheduling request and waiting for a grant for every transmission, can be avoided. This reduces not only the delay, but also the dependence of error-prone control signaling for URLLC. For reducing the resource wastage caused by sporadic URLLC transmissions, the base station (BS) can configure the same resources to multiple user equipments (UE). However, this leads to augmented intra-cell interference when transmissions overlap. The problem becomes more evident if the grant-free resources are overlaid for multiplexing abundant eMBB traffic. Since it is not known a priori when a sporadic URLLC transmission will occur, it is not possible to timely interrupt an ongoing transmission for avoiding a collision, potentially degrading the reliability.

Different studies have considered the problem of multiplexing heterogeneous traffic in uplink. In [6], a joint eMBB and URLLC scheduler is proposed, with superposition of ongoing transmissions. The overlaying multiplexing between resource greedy broadband traffic and sporadic small data is considered in [7] and evaluated with basic information theoretical tools for a single cell scenario. An heterogeneous non-orthogonal multiple access approach is studied in [8] using a theoretic model, however, multiple URLLC transmissions over the shared resource are not considered. In [9], a theoretical analysis of overlaying versus separate allocation is presented. Minimum-mean square error (MMSE) is considered for the reception of multiple URLLC and eMBB transmissions. Detailed analysis considering the aspects of a multi-cell 5G NR system are not considered in previous works.

In this work we present system level performance evaluation for the inter-UE multiplexing of eMBB and URLLC uplink transmissions. We consider the case of sporadic grant-free URLLC, with shared resource allocations, overlaying with full-buffer eMBB streams, in a multi-cell system. We discuss the aspects of open loop power control and identify the criteria for setting the relevant parameters in order to manage the trade-off between URLLC reliability and eMBB capacity. Results from detailed simulation campaigns following 5G NR assumptions are presented in terms of URLLC outage probability and eMBB SINR.

The reminder of the work is organized as follows. The considered system is presented in Section II and the power control aspects in Section III. Section IV describes the methodology and assumptions. Results are presented in Section V and discussed in Section VI. Section VII concludes the paper.

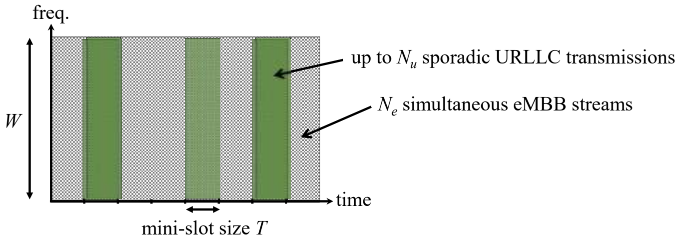


Fig. 1. Overlaying eMBB and grant-free URLLC allocations in a cell.

II. SYSTEM MODEL

We consider a multi-cell radio network composed of C cells with synchronized base stations (BS). A fixed number of URLLC UEs N_u are deployed in each cell. Besides, N_e eMBB UEs can be active in the same cell. The UEs are considered to be connected and synchronized with the serving BS for their uplink data transmission. Fig. 1 illustrates the considered multiplexing scheme. The eMBB UEs are assumed to have a large amount of data to transmit. Their traffic follows a full buffer model, ensuring a permanent flow of eMBB data to be scheduled over the time slots. The N_e eMBB UEs are scheduled over the full carrier bandwidth W. The BS exploits then multi-user reception capability by employing an M_r antennas receiver, for retrieving overlaying signals.

The URLLC UEs have sporadic traffic consisted of small payloads of size B. Such traffic is modeled as a Poisson arrival process with packet arrival rate λ. In order to serve the URLLC traffic with minimum latency, a short-TTI of duration T is employed. The serving BS configures also the URLLC UEs to transmit with grant-free resources over the bandwidth W. We assume that the N_u UEs share the same resource configuration, therefore their transmissions are susceptible to mutual collisions, in addition to the interference from eMBB traffic being multiplexed over the same resources. A wide-band allocation allows harvesting frequency diversity. It also permits the use of a robust modulation and coding scheme (MCS) to cope with fading and potential interference from simultaneous transmissions.

A linear minimum-mean square error with interference rejection combining (MMSE-IRC) receiver is assumed in the BS. Since the UEs and the BSs are fully synchronized, it permits the receiver to take into account intra- and inter-cell interference signals for computing the interference covariance matrix. Then, the MMSE-IRC receiver operates on the degrees of freedom offered by the multiple receive antennas to retrieve multiple overlaid transmissions. Still, in case the interference level is too severe the reception can be compromised. This motivates the use of careful power control settings for reducing the penalty in the URLLC reliability or eMBB capacity.

III. POWER CONTROL SETTING FOR OVERLAYING TRANSMISSIONS

The 3GPP Release-15 specification defines the power control for the uplink channels in [10]. The transmit power (in dBm) over the physical uplink shared channel (PUSCH) is described, in simplified notation, as

$$P = min\begin{cases} P_{max} \\ P_0 + 10log_{10}(2^{\mu}M) + \alpha PL + \Delta_{mcs} + f(i) \end{cases}, \quad (1)$$

where P_{max} is the maximum transmit power of the UE, P_0 is a UE specific parameter related to the power per resource block (RB), the exponent μ is set according the sub-carrier spacing (0 for 15 kHz, 1 for 30 kHz, and so on), M is the number of RBs allocated, α is a path-loss compensation factor, PL is the estimated path-loss between the UE and the BS. Δ_{MCS} is a quality requirement parameter depending on the MCS that can be configured by upper layers and $f(i)$ is a parameter for closed loop power control adjustments; these were not considered in this study.

The use of fractional power control is known for improving the capacity for broadband communication [11]. For such, $\alpha < 1$ is applied, as well as a correspondent increase in P_0, improving the SINR, and hence, the throughput of cell center UEs. However, as discussed in [12], the usage of full path-loss compensation is more attractive for URLLC to avoid an outage penalty in cell edge. In the case of overlaying allocations, the performance of eMBB and URLLC presents a trade-off, i.e. power control settings that benefits eMBB penalizes URLLC and vice-versa. Thus, in our proposal the settings are applied on a service basis. With that, eMBB UEs are configured with P_0^e and α^e, while URLLC UEs are configured with P_0^u and α^u. Here we assume that, for each service, all UEs in the cell use the same parameters. These parameters should be carefully selected for meeting the service requirements. As a simple example, for $\alpha^u = \alpha^e$ setting $P_0^e >> P_0^u$ potentially increases the interference of eMBB over URLLC compromising the reliability. While $P_0^e << P_0^u$ can deteriorate the eMBB capacity.

IV. EVALUATION METHODOLOGY

The impact on the performance of overlaying grant-free URLLC and eMBB is evaluated through extensive system level simulations for different power control settings. The evaluation methodology is based on NR assumptions as defined in [13]. The simulator uses commonly accepted models and is calibrated according to 3GPP NR guidelines [14]. The main parameters for the network configuration and the main simulation assumptions are summarized in Table I.

A 3D urban macro scenario is assumed, consisting of $C = 21$ synchronized cells (7 sites with 3 sectors each). The inter-site distance is 500 meters. World wrap around is used for avoiding edge effects. We consider different load conditions for URLLC. For low load, 10 URLLC UEs per cell are uniformly distributed in the scenario. And for high load, 300 URLLC UEs per cell are distributed. Each URLLC UE transmits payloads of $B = 32$ bytes following a Poisson arrival process with average arrival interval of 100 ms, i.e. $\lambda = 10$ packets per second. This leads to a load $L = 25.6$ kbps per cell for low URLLC load, and $L = 768$ kbps for high URLLC load. One and two eMBB UEs are also deployed in each cell, equivalent to a single stream and two multi-user MIMO streams. The eMBB UEs use full-buffer traffic model,

TABLE I
SIMULATION ASSUMPTIONS

Parameters	Assumption
Layout	Hexagonal grid with 21 cells (7 sites and 3 sectors/site), world wrap-around
Inter-site distance	500 meters
Carrier frequency	$4\,\text{GHz}$
Channel model	3D Urban Macro (UMa)
UE distribution	Uniformly distributed outdoor, $3\,\text{km/h}$ UE speed fading model
UE transmitter	$P_{max} = 23\,\text{dBm}$, $M_t = 1$ transmit antenna
BS receiver	MMSE-IRC, $M_r = 4$ receive antennas
Receiver noise figure	$5\,\text{dB}$
Thermal noise	$-174\,\text{dBm/Hz}$
Bandwidth	$W = 10\,\text{MHz}$ in uplink, FDD
PHY configuration	$15\,\text{kHz}$ sub-carrier spacing, 2 symbols mini-slot ($T = 0.143\,\text{ms}$), 12 sub-carriers/RB
Grant-free configuration	MCS QPSK1/8, periodicity of 2 symbols, $M = 48$ RBs for uplink data, HARQ disabled
eMBB UEs per cell	0 (no eMBB interference baseline), 1 (single stream) and 2 (MU-MIMO streams)
eMBB traffic model	full-buffer
URLLC UEs per cell	10 for low load, and 300 for high load
URLLC traffic model	FTP Model 3, $B = 32$ bytes, Poisson arrival rate of $\lambda = 10$ packets per second per UE

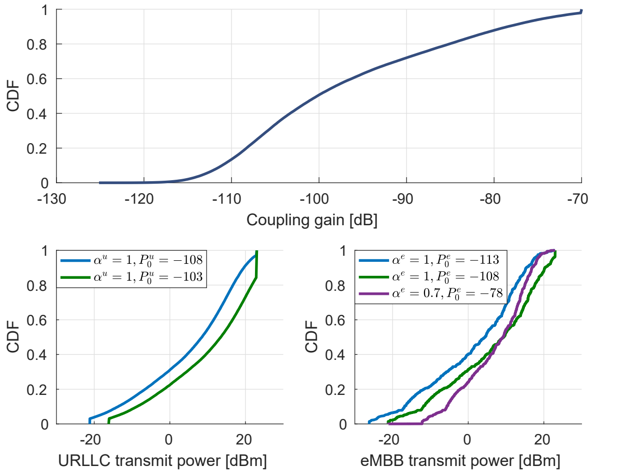


Fig. 2. Coupling gain distribution in evaluated urban macro scenario outdoor (top). Transmit power distribution for URLLC UEs (bottom left), and eMBB UEs (bottom right).

being continuously scheduled over the full bandwidth. The UEs are deployed at the beginning of the simulation drop. Each UE connects to the cell with highest reference signal received power (RSRP) and remains in connected state until the simulation finishes.

The URLLC UEs are configured for transmission in mini-slots of 2 OFDM symbols, with sub-carrier spacing of $15\,\text{kHz}$ which leads to a $T = 0.143\,\text{ms}$ TTI. The allocation for grant-free transmissions uses a bandwidth $W = 10\,\text{MHz}$, giving $M = 48$ RBs for data, with 2 symbols periodicity. This allows a transmission opportunity in full-band at every TTI in order to minimize latency. The grant-free transmissions use a conservative MCS QPSK 1/8, fitting the 32 bytes payload in one-shot transmission without segmentation. Considering latest processing time assumptions (capability 2 in [10]), a transmission can be received and processed within $1\,\text{ms}$. HARQ retransmissions are not considered.

The BSs are equipped with MMSE-IRC with $M_r = 4$ receive antennas. Channel estimation is assumed ideal for the desired and interference signals. The successful reception of a packet depends on the obtained post-processing SINR at the receiver and the used MCS. For every detected transmission, the post-processing SINR after the MMSE-IRC receiver combining is calculated for each sub-carrier. That is used to compute the symbol-level mutual information metric according to the applied modulation as described in [15]. Then, given the used code rate, a look-up table obtained from extensive link level simulations is used to map the metric value to a block error probability.

Multiple simulation drops are executed for collecting 5 million URLLC transmission samples, in order to obtain statistically significant results in the low quantiles [16]. The main key performance indicator analyzed for URLLC is the outage probability, i.e. the complement of the reliability (targeting 10^{-5}). The latency of each transmission is used for determining an empirical complementary cumulative distribution functions (CCDF). The outage probability is then read at the $1\,\text{ms}$ from the latency CCDF. For the eMBB performance, we collect the 5th percentile and the 50th percentile SINR values. These reference metrics indicate the cell edge and the near to average performance, respectively.

V. PERFORMANCE EVALUATION

The power control settings P_0 and α for eMBB and URLLC UEs were varied for the different simulation campaigns, in which were collected the one-way latency of the URLLC packets and the SINR of the eMBB transmissions. The power control settings for URLLC were chosen as the ones that allow the highest URLLC load while fulfilling the requirements [12]. Full path-loss compensation is used for URLLC, i.e. $\alpha^u = 1$. For eMBB, full and fractional path-loss compensation are used, i.e. $\alpha^e = 1$ and $\alpha^e = 0.7$ respectively. The P_0 values are set equal or lower than the URLLC ones, except when fractional path-loss compensation is used. For reference, the empirical cumulative distribution function (CDF) of the coupling gain for the evaluated outdoor scenario is shown in Fig. 2. The CDFs of the URLLC and the eMBB transmit power are also shown for each utilized setting. For both, URLLC and eMBB using $\alpha^u = \alpha^e = 1$ and $P_0^u = P_0^e = -108\,\text{dBm}$, 3% of the UEs transmit with maximum power P_{max}. For URLLC configured with conservative power control settings, $\alpha^u = 1$ and $P_0^u = -103\,\text{dBm}$, 15% of the URLLC UEs transmit with P_{max}. For eMBB with $\alpha^e = 0.7$ and $P_0^e = -78\,\text{dBm}$, as well as with $\alpha^e = 1$ and $P_0^e = -113\,\text{dBm}$, virtually no eMBB UE reaches P_{max}.

Fig.3 shows the outage probability for the case of 10 URLLC UEs per cell, with their transmissions being multiplexed with 1 and with 2 eMBB interferer streams. Baseline cases without eMBB interference are also shown as “eMBB off”. It is observed that the URLLC target is satisfied if no eMBB UEs are present, leading to an outage probability $< 10^{-6}$. Reducing the power of eMBB with $P_0^e = -113\,\text{dBm}$

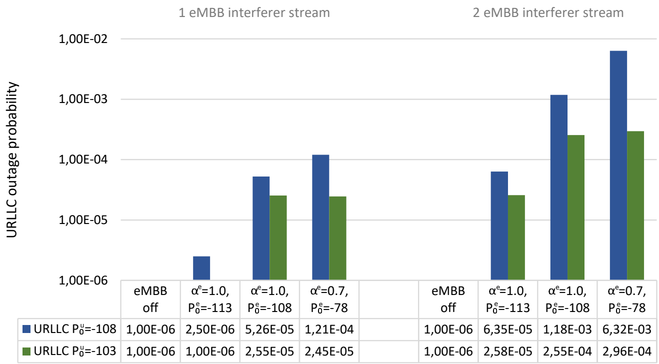


Fig. 3. Outage probability of grant-free URLLC for $L = 25.6\,\text{kbps}$.

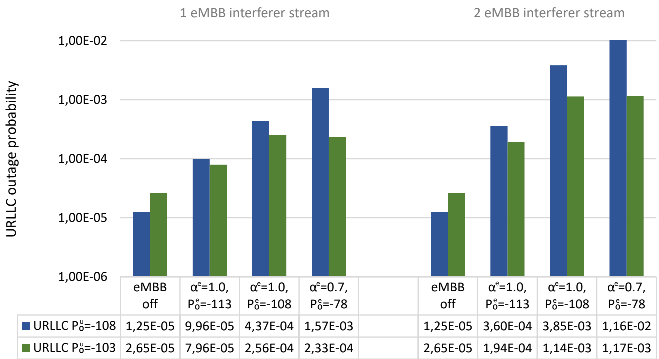


Fig. 4. Outage probability of grant-free URLLC for $L = 768\,\text{kbps}$.

(i.e. $5\,\text{dB}$ lower than for the URLLC UE) also allows URLLC to reach the target, when only 1 eMBB stream is present. For the cases where eMBB uses the same power control settings as URLLC, the outage probability rises to the order of 10^{-4}. With 2 simultaneous eMBB streams, the penalty for URLLC is obviously higher due to the increased interference. The use of fractional path-loss compensation for eMBB does not help, since the cell center eMBB UEs generates higher intra-cell interference. The outage probability for high URLLC load, with 300 URLLC UEs per cell, is shown in Fig.4. In this case the URLLC requirement is nearly met only when eMBB UEs are not transmitting, i.e. without eMBB interference a URLLC load of $\approx 0.77\,\text{Mbps}$ per cell is supported. However, the outage probability of URLLC increases by a factor of 10 to 100 when eMBB is present. For both load situations, the use of a high P_0^u makes URLLC more robust to the presence of eMBB interference. However, when eMBB is not present, the lower P_0^u results in a lower outage due to reduced interference among URLLC UEs. Using lower P_0^e values reduces the impact on URLLC, however it comes with the cost of lower SINR for eMBB, which converts to a capacity loss.

Fig.5 and Fig.6 shows the impact on the eMBB SINR for the different power control settings. For the lower URLLC load there is little difference on eMBB performance for the different URLLC P_0^u settings. As expected, the eMBB SINR is low in the case of a low P_0^e. And from full to fractional path-loss compensation, there is an improvement in the 50th percentile SINR and a degradation in the 5th percentile SINR. The same observation can be drawn for one and for two eMBB streams. With the higher URLLC load there is a clear impact in the eMBB SINR (up to $3.1\,\text{dB}$ for $P_0^u = -108\,\text{dBm}$). Besides, the $5\,\text{dB}$ increase in P_0^u, causes up to $1.67\,\text{dB}$ of degradation in eMBB SINR. The low 5th percentile SINR values, getting down to $-5\,\text{dB}$, indicates the very limited eMBB capacity in the cell edge even with high P_0^e.

It is worth to mention that the resource utilization without eMBB, for low URLLC load is 1.4%, and for high URLLC load is 35%. This means that a big share of the resources is wasted in detriment of URLLC. This demonstrates the importance of multiplexing eMBB together with the URLLC traffic for the feasibility of the 5G system.

VI. Discussion

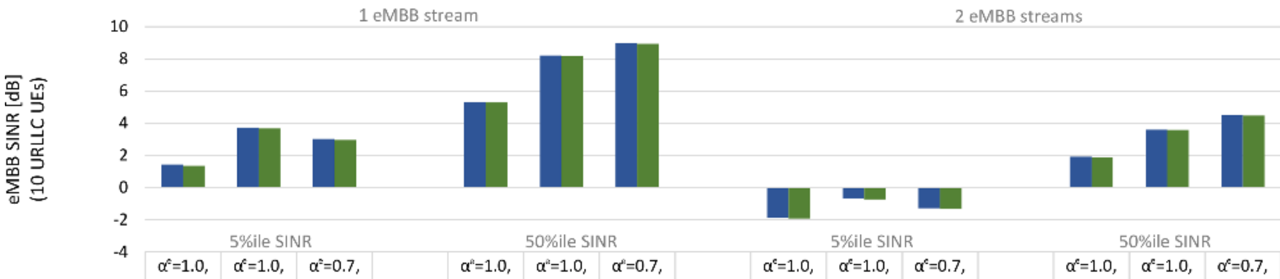
It is worth noting that, despite the potential of fractional path-loss compensation for improving eMBB average throughput, cell center eMBB UEs with elevated transmit power further penalizes the URLLC transmissions. Therefore, full path-loss compensation and lower P_0 values should be also preferred for eMBB when multiplexing with URLLC.

The presence of a high URLLC load in the cell imposes a reduced capacity for eMBB. The use of the receiver capability for MU-MIMO is compromised due to the limitation on degrees of freedom for suppressing all the mutual interference. The system performance can be enhanced e.g., by utilizing MMSE-IRC with higher number of antennas, which improves the diversity order and interference rejection capability. Besides, successive interference cancellation (SIC) can be employed for subtracting the signal from decoded URLLC transmissions from the received signal. This can mainly reduce the interference over the eMBB transmissions [8], [9].

For applications in which the latency requirement can be relaxed, preemption schemes enabled by dynamic downlink control signal should be preferred [17]. Those are able to interrupt on-going eMBB transmissions for scheduling URLLC data. eMBB can be potentially resumed after the URLLC transmission. With that, both URLLC and eMBB should be benefited from the reduced interference. Besides, dynamic scheduling permits accurate resource allocation and adaptation per-user transmission basis. This results in guaranteed quality of service with efficient usage of resources.

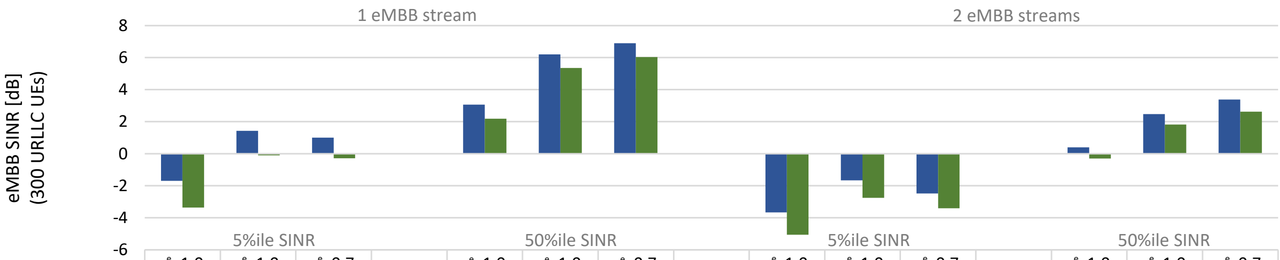
VII. Conclusions

In this paper, we studied the performance of grant-free URLLC and eMBB multiplexing in uplink. We considered the overlaying of eMBB transmissions with the grant-free URLLC transmissions over the same resources. Different uplink transmit power control settings are proposed for managing the trade-off between the URLLC outage probability and the eMBB capacity. Detailed evaluation of the settings was conducted through extensive system level simulations following 5G NR assumptions. We observe that overlaying URLLC and eMBB transmissions is only feasible for low URLLC loads (e.g. $0.26\,\text{Mbps}$). Even though, it requires restrictions which impose severe performance loss for eMBB, such as, reduced capability for co-scheduling users and $5\,\text{dB}$ lower P_0 value.



	5%ile SINR (1 eMBB stream)			50%ile SINR (1 eMBB stream)			5%ile SINR (2 eMBB streams)			50%ile SINR (2 eMBB streams)		
	α^e=1.0, P_0^e=-113	α^e=1.0, P_0^e=-108	α^e=0.7, P_0^e=-78	α^e=1.0, P_0^e=-113	α^e=1.0, P_0^e=-108	α^e=0.7, P_0^e=-78	α^e=1.0, P_0^e=-113	α^e=1.0, P_0^e=-108	α^e=0.7, P_0^e=-78	α^e=1.0, P_0^e=-113	α^e=1.0, P_0^e=-108	α^e=0.7, P_0^e=-78
URLLC P_0^u=-108	1,43	3,73	3,02	5,31	8,21	8,96	-1,87	-0,69	-1,28	1,91	3,6	4,51
URLLC P_0^u=-103	1,36	3,67	2,97	5,28	8,18	8,93	-1,92	-0,73	-1,32	1,88	3,58	4,48

Fig. 5. eMBB SINR with grant-free URLLC load of $L = 25.6\,\text{kbps}$.



	5%ile SINR (1 eMBB stream)			50%ile SINR (1 eMBB stream)			5%ile SINR (2 eMBB streams)			50%ile SINR (2 eMBB streams)		
	α^e=1.0, P_0^e=-113	α^e=1.0, P_0^e=-108	α^e=0.7, P_0^e=-78	α^e=1.0, P_0^e=-113	α^e=1.0, P_0^e=-108	α^e=0.7, P_0^e=-78	α^e=1.0, P_0^e=-113	α^e=1.0, P_0^e=-108	α^e=0.7, P_0^e=-78	α^e=1.0, P_0^e=-113	α^e=1.0, P_0^e=-108	α^e=0.7, P_0^e=-78
URLLC P_0^u=-108	-1,69	1,43	1,01	3,06	6,21	6,9	-3,66	-1,66	-2,48	0,4	2,47	3,38
URLLC P_0^u=-103	-3,36	-0,1	-0,28	2,19	5,36	6,04	-5,06	-2,75	-3,41	-0,3	1,82	2,63

Fig. 6. eMBB SINR with grant-free URLLC load of $L = 768\,\text{kbps}$.

Higher URLLC load of e.g. $\approx 0.77\,\text{Mbps}$ is supported when no eMBB UE is multiplexed over the same resources. However it results in a poor resource utilization (35%). The insights obtained for the power control configuration can be utilized as reference for the setup of 5G deployments with heterogeneous services. The results demonstrate the severe penalty caused by eMBB transmissions over URLLC. This motivates the application of preemption mechanisms for avoiding collisions when URLLC traffic can be dynamic scheduled.

Future work should consider dynamic scheduling solutions of the uplink URLLC transmissions suspending on-going eMBB transmissions, as well as the impacts of the control channel overhead and imperfections.

VIII. Acknowledgments

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