

# Capacity Cost of Fulfilling the URLLC Performance in Industrial 5G New Radio Deployments

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**Abstract**—The development of the 5G new radio specifications has been derived by the deterministic low latency use-cases such as the ultra-reliable and low-latency communications (URLLC). A URLLC application requires a stringent radio latency and reliability performance, e.g., one-way radio latency of 1 ms with 99.999% success probability. Furthermore, there is a concurrent progressive demand for broadband capacity cellular applications, e.g., enhanced mobile broadband (eMBB) use-cases. The coexistence among the URLLC and eMBB service classes over a single radio spectrum is a challenging task since achieving the tight URLLC radio targets typically results in a capacity loss. Hence, it is vital for telecom operators to understand the capacity cost of fulfilling the various URLLC requirements in order to sufficiently plan the corresponding pricing models. Hence, in this work, a comprehensive analysis of the system capacity loss is presented to achieve the various requirements of the different URLLC use-cases. An extensive set of realistic system level simulations is performed and introduced where valuable insights and system design recommendations on the URLLC-eMBB quality of service coexistence are presented.

**Index Terms**—5G new radio; Indoor factory automation (InF); URLLC; eMBB; 3GPP.

## I. INTRODUCTION

Unlike the former radio network generations, the fifth generation (5G) new radio (NR) specifications support revolutionary multi quality-of-service (QoS) classes such as the ultra-reliable low-latency communications (URLLC), and the enhanced mobile broadband (eMBB) [1]. The URLLC applications demand a stringent set of the radio latency and reliability targets while the eMBB services demand broadband communication data rates [2]. This multi-QoS-class coexistence enables novel cellular applications and use-cases, e.g., tactile internet, true smart infrastructures, and virtual reality communications [3].

However, the deterministic low-latency industrial applications, i.e., industry 4.0 deployments [4, 5], are the lead drivers of the 5G and 5G-advanced (release-18 and beyond) developments. Within those deployments, a wide range of, though, conflicting, QoS classes, radio performance requirements, and device types should be supported. That is, a deterministic ultra-low radio latency with a certain reliability level is always guaranteed while a pre-determined capacity/data rate target(s) should be preserved for simultaneous capacity demanding services [6]. Fundamentally, achieving an ultra-low radio latency leads to an insufficient radio capacity of the same communication bandwidth. Thus, it is of a significant importance for telecom operators and cellular service providers to identify the system capacity cost, which is paid/lost in order

to fulfill a certain ultra-low latency service performance target, and hence, adapt their pricing models accordingly.

In the state-of-the-art open literature, there are many contributions of MAC and PHY schemes that trade-off the achievable system capacity with the lowest guaranteed radio latency. Examples include reinforcement learning based link adaptation for a faster URLLC packet transmission [7, 8], QoS-aware scheduling schemes [9], and on-the-fly resource preemption techniques [1, 10]. Those proposals seek to achieve a guaranteed maximum radio latency for the URLLC critical services while maximizing the overall system capacity, i.e., by incurring the minimum possible capacity loss of the eMBB traffic.

In this paper, a comprehensive analysis of the capacity loss, due to fulfilling a certain URLLC latency and reliability performance target, is presented. Various URLLC latency and reliability targets are considered to match the different URLLC use-cases and deployments. The reference case considered in this work is the best effort eMBB, where the corresponding radio latency performance is relaxed. Thus, the paper answers the following question: "what is the system capacity lost, compared to the best effort case, to satisfy a guaranteed maximum URLLC radio latency with a certain radio reliability level?". An extensive set of realistic system level simulations is performed to obtain a set of statistically reliable results and the respective conclusions.

This paper is organized as follows. Section II presents the system model and the main performance indicator considered in this work. Section III introduces the simulation methodology and the performance results. Section IV presents the acknowledgments and Section IV concludes the paper.

## II. SYSTEM MODEL

### A. Setting the scene

In this work, we consider an industrial factory automation deployment with  $C$  indoor cells, horizontally inter-distanced by  $d = 20$  meters, as shown by Fig. 1. Each cell serves an average number of  $K$  uniformly distributed user-equipment's (UEs), where even UE dropping for all cells is adopted. In this study, we assume only downlink (DL) traffic towards active UEs. To emulate the URLLC use cases, the traffic is characterized by the FTP3 traffic model, where data packets of a finite payload size  $B$ -Bytes are considered. The DL packets arrive at the cell following a Poisson Arrival Process with a predefined mean arrival rate  $\lambda$  (packets/sec). Therefore,

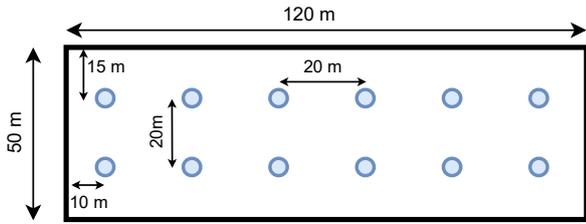


Figure 1. Industrial factory deployment.

the total offered load  $\Omega$  in bits/sec for the entire factory deployment is calculated as:

$$\Omega = C \times (K \times B \times 8 \times \lambda). \quad (1)$$

We follow the 3GPP assumptions and guidelines for URLLC simulations. URLLC UEs are dynamically multiplexed using the orthogonal frequency division multiplexing (OFDMA). The 30 kHz numerology (i.e., sub-carrier spacing) is used in this work, in line with [1], since it offers a sufficiently short OFDM symbol duration in order to fulfill the stringent radio latency requirements of the URLLC services. The minimum schedulable resource unit is the physical resource block (PRB), consisting of 12 successive sub-carriers. Moreover, we consider a short transmission time interval (TTI) duration of 4 OFDM symbols for faster URLLC transmission and scheduling.

Thus, an arriving DL packet is processed as follows: the packet is first received and prepared for transmission by the serving cell RF stack processor. The delay consumed before the DL transport block is ready for transmission is taken explicitly into account in this study, in line with [2]. Then, the dynamic scheduler of the serving cell multiplexes all pending DL packets for transmission, using the proportional fair (PF) scheduling criterion. Hence, packets of the highest PF metric, are transmitted during the current TTI interval while other packets are further buffered towards the upcoming scheduling instants, i.e., queuing delay of the dynamic scheduling. We consider an adaptive modulation and coding selection (MCS) corresponding to a first-transmission block error rate (BLER) of 1%. Therefore, the MCS level is dynamically selected based on the latest reported channel quality indication (CQI) from each UE.

Accordingly, the serving cell sends a scheduling grant, using the lower-layer downlink control information (DCI) signaling, to notify the corresponding UEs of the DL resource allocations. The resource overhead of the physical-layer control signaling is explicitly taken into account; however, in this work, we assume the delay of transmitting and processing the scheduling grants is negligible. At the UE side, the delay consumed to process and decode received DL packets is explicitly considered into account of the total radio latency. If the transmitted DL packet is not successfully decoded at the UE, the UE sends a hybrid automatic repeat request (HARQ) negative acknowledgment (NACK). The delay for transmitting the HARQ feedback for each packet is also explicitly considered. In such case, the serving cell re-transmits the respective

packet for soft-combining at the UE side. At the cell side, the HARQ re-transmissions are always prioritized over new packet transmission in order to reduce the overall radio latency for pending packets.

### B. Main performance metric indicators (KPIs)

The major KPIs of this work are the achievable one-way URLLC outage latency and the corresponding network throughput/capacity, respectively. Thus, the total radio latency of each DL packet  $\varphi$  is measured and tracked, for various outage probabilities  $\rho$ . In particular, the considered latency metric denotes the delay from the moment a DL packet is generated and arrives at the packet data convergence protocol (PDCP) layer of the serving cell until it is successfully decoded at the intended UE. This sums up the cell and UE processing delays, the transmission delay, the dynamic scheduling queuing delay, and HARQ re-transmission delay, respectively. Therefore, for a certain target outage probability, we present the maximum supported offered load/capacity of the network such as to fulfill a maximum guaranteed URLLC radio latency.

Furthermore, in this work, we adopt the throughput cost metric  $\Psi$  of the URLLC and best effort (BE) cases, respectively. The BE case denotes the transmissions of an infinite packet size and without a target outage latency requirement such that the network capacity is maximized. Hence, the cost metric implies how much network throughput is lost (paid) in order to fulfill a certain URLLC outage latency target, compared to the achievable network throughput of the BE case, and is calculated as follows:

$$\Psi(B, \varphi, \rho) = \left(1 - \frac{\mu_{urllc}(B, \varphi, \rho)}{\mu_{BE}}\right) \times 100\%, \quad (2)$$

where  $\Psi(B, \varphi, \rho)$  denotes the inflicted network throughput cost of the URLLC use cases, with a packet size of B-Bytes in order to fulfill a maximum guaranteed radio latency of  $\varphi$  ms for the target outage probability  $\rho$ .  $\mu_{urllc}$  and  $\mu_{BE}$  are the achievable mean network throughput metrics of the URLLC and BE cases, respectively.

## III. PERFORMANCE EVALUATION

### A. Simulation Methodology

We comprehensively evaluate the performance of the URLLC service class using extensive system level simulations. The major system settings are presented in Table I. The conducted simulations follow the system modeling assumptions, presented in Section II, and the general 3GPP simulation methodology. The industrial factory deployment layout is considered alongside with employing the state of the art industrial factory channel model. Dynamic FTP3 traffic arrivals are considered at each UE, where the arrival rate follows a Poisson Point Arrival Process. When a UE is created, it connects to the surrounding cell with the highest received reference signal power (RSRP). The simulations explicitly include the major functionalities of the PHY and MAC stack layers. For each transmitted packet, the sub-carrier signal to interference noise ratio (SINR) is calculated using the

Table I  
SIMULATION PARAMETERS.

Parameter	Value
Environment	3GPP-InF, one cluster, 12 cells
DL channel bandwidth	40 MHz, SCS = 30 KHz, FDD
Channel model	InF-DH (dense clutter and high BS) [11]
BS transmit power	BS: 25 dBm
Carrier frequency	4 GHz
BS heights	BS: 10m
Antenna setup	2x2
Average UEs per cell	10
TTI configuration	4-OFDM symbols
URLLC Traffic model	FTP3, packet size = 50/1500 Bytes
eMBB Traffic model	Best effort with infinite payload size
DL scheduling	proportional fair
Processing time	PDSCH prep. delay: 2.5-OFDM symbols PDSCH decoding : 4.5-OFDM symbols
DL receiver	L-MMSE-IRC

linear minimum mean squared error interference rejection and combining (LMMSE-IRC) receiver. The effective SINR is calculated by combining the estimated sub-carrier SINRs using the mean mutual information per coded bit (MMIB) mapping. Based on the effective SINR, the packet error probability (PEP) is calculated from predefined look-up tables, obtained from extensive link level simulations. Therefore, based on PEP, the packet is determined as successfully received or not. If the packet is not successfully decoded from first transmission, the corresponding HARQ re-transmissions are triggered. Every DL TTI, UEs are dynamically scheduled based on the proportional fair criterion. The corresponding modulation and coding scheme (MCS) is selected based on the latest available channel quality indicator (CQI) reports.

Finally, the simulator is periodically calibrated by reporting and comparing baseline performance statistics among the 3GPP partners. Moreover, in line with [2], we run simulations for a sufficiently long period of time in order to ensure high statistical confidence of the achievable results before drawing solid conclusions. That is, the default simulation time is at least 5 million successfully-decoded URLLC packets.

### B. Performance Results

In this section, we mainly evaluate the inflicted network capacity loss in order to fulfill certain URLLC outage latency targets. In particular, the maximum supported offered capacity is investigated for URLLC and best effort cases, respectively. The URLLC services are evaluated to achieve various outage latency targets. That is, for different maximum guaranteed radio latency budgets for several outage probability levels, and using two payload sizes (50 and 1500 Bytes). The best effort reference denotes the case where the requirement on the radio latency is relaxed, and is evaluated under two different UE schedulers: the proportional fair (PF) and equal throughput (ET) schedulers, respectively. The former enables a fair scheduling criterion without an inter-UE throughput regularization while the latter seeks to achieve a guaranteed equal throughput per UE.

Fig. 2 depicts the maximum supported offered load of the URLLC traffic, with a large 1500-byte payload size, to achieve a maximum guaranteed outage latency of 1, 3 and

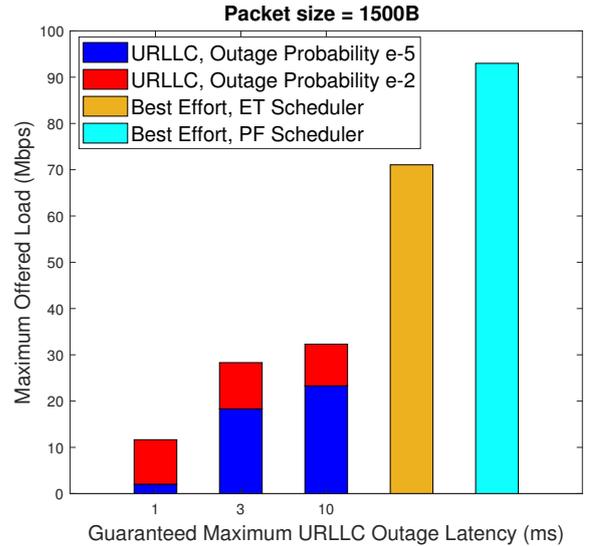


Figure 2. URLLC outage latency performance, large payload case.

10 ms, respectively, and under various outage probabilities as  $10^{-5}$  and  $10^{-2}$ . As can be noticed, achieving the 1 ms latency deadline with  $10^{-5}$  outage probability significantly degrades the achievable capacity compared to both cases of the best effort class, with PF and ET schedulers, respectively. That is, to achieve a maximum guaranteed 1 ms of the radio latency, the maximum supported offered loads are 2.03 Mbps and 11.65 Mbps for the  $10^{-5}$  and  $10^{-2}$  outage probabilities, compared to 71.06 Mbps and 93 Mbps with the best effort case of the ET and PF packet schedulers. Furthermore, the best effort case with ET scheduler clearly exhibits  $\sim 23.6\%$  reduction of the achievable capacity compared to the case with the PF scheduler, due to sacrificing part of the system capacity in order to guarantee an equal-UE perceived throughput.

Looking at the case of the URLLC small payload, Fig. 3 shows the achievable load performance of the 50-byte URLLC case, where similar conclusions as of Fig. 1 are observed. Relaxing the stringent requirement of the outage probability offers a clear capacity improvement over the low radio latency region. For instance, to achieve a maximum guaranteed 1-ms target, the supported offered capacity is improved by  $\sim 76.4\%$  with the  $10^{-2}$  outage probability, compared to that is of the  $10^{-5}$  outage level.

The packet size is deemed to have a vital impact on the achievable joint outage latency and capacity performance. Therefore, Fig. 4 depicts a capacity comparison of the URLLC class with small and large payload sizes, i.e., 50 and 1500 bytes, respectively, at the  $10^{-5}$  outage probability. As clearly seen, the small packet transmissions are observed to be more efficient in supporting more offered capacity to achieve the same outage latency target, compared to that is of the large payload. For instance, to achieve the stringent 1-ms latency target, the small-payload transmissions supports  $\sim 56.4\%$  more offered load than the large-payload case.

This is mainly attributed to the required multiple resource allocations over multiple TTIs for the large-size packets to

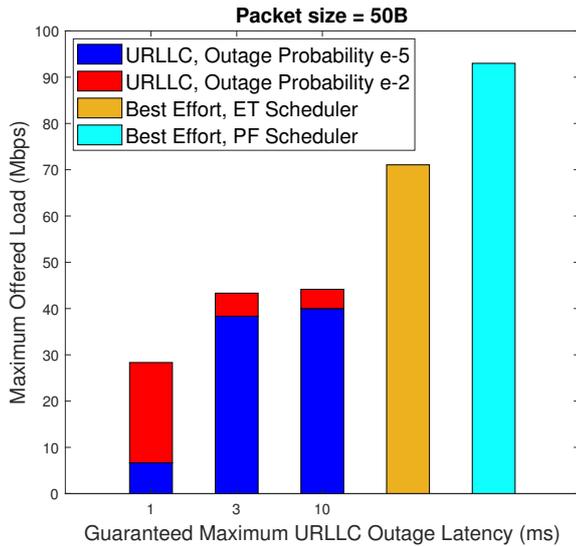


Figure 3. URLLC outage latency performance, small payload case.

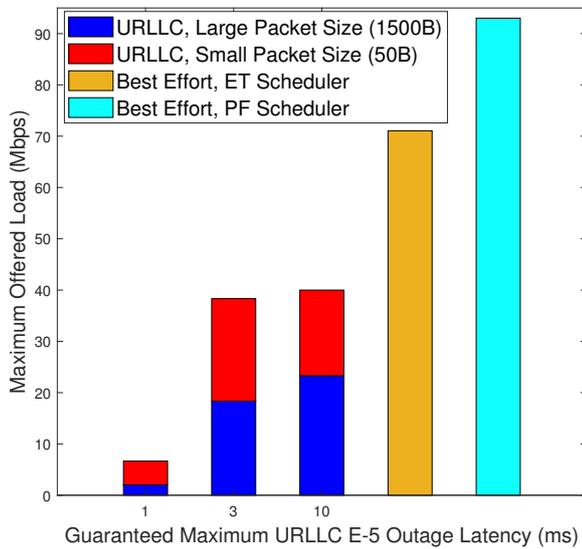


Figure 4. URLLC outage latency performance, with payload size.

get fully transmitted. Fig. 5 depicts the empirical cumulative distribution function (ECDF) of the total number of scheduled PRBs per each FTP3 packet, for different supported offered load levels, which correspond to a certain maximum guaranteed outage latency, i.e., 1, 1.5, and 3 ms radio latency targets, respectively, at the  $10^{-5}$  outage probability. At the 50%ile level, a single 1500-byte URLLC packet requires 63 and 78 PRBs (out of total 100 PRBs) of a single TTI, respectively, for the three latency targets under evaluation to be fulfilled. This implies a maximum of a single packet transmission per TTI while the other concurrent packets from other active UE are being buffered towards the upcoming transmission opportunities. However, at the tail distribution, i.e., 95%ile level, for the offered loads of 70 and 220 Mbps, respectively, a single FTP3 packet requires 138 and 237 PRBs, respectively.

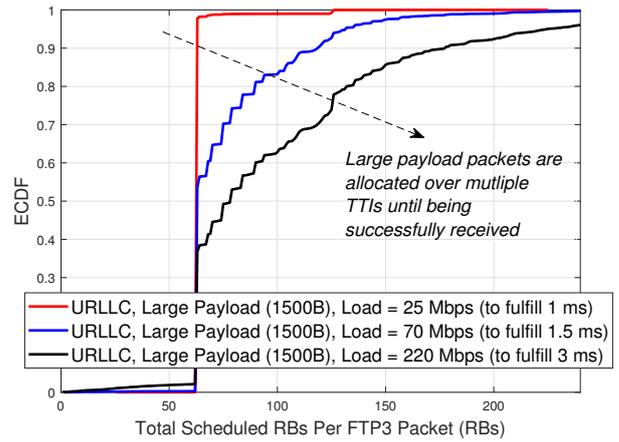


Figure 5. Resource utilization performance of the URLLC large packets, for different outage latency targets.

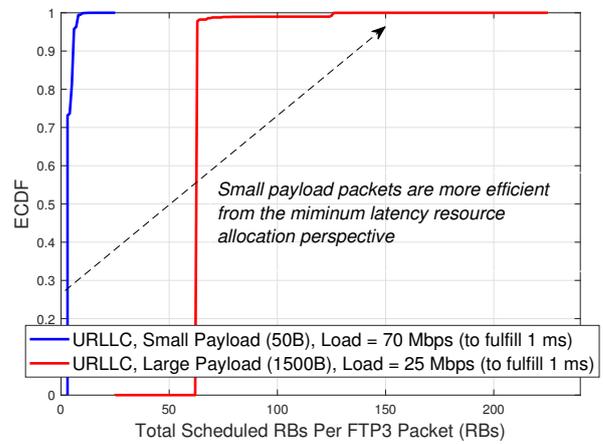


Figure 6. URLLC resource utilization performance, for small and large payload packets.

This denotes that a single 1500-byte packet is scheduled over multiple TTIs, consuming most of the available bandwidth. This is particularly relevant to the packets from the cell-edge UEs, where their decoding ability is highly deteriorated due to the strong inter-cell interference. Thus, to achieve the target 1% BLER, the serving BS relies on a conservative MCS selection for the respective packet transmissions, leading to a significant degradation of the network spectral efficiency.

On the opposite side, and as shown by Fig. 6, the small-payload URLLC transmissions, i.e., 50-byte payload, are more efficient than the large 1500-byte payload from the minimum-delay allocation perspective. To fulfill the stringent 1-ms latency target at the  $10^{-5}$  outage probability, the small-payload transmissions require 3 PRBs on average compared to 63 PRBs with the large payload. This allows for: (a) scheduling the entire small-payload URLLC packets within a single TTI duration without segmentation, and (b) co-scheduling multiple packets from multiple active UEs at the same TTI, hence, reducing the average packet queuing delay accordingly.

Finally, Fig. 7 and 8 show the overall throughput cost of

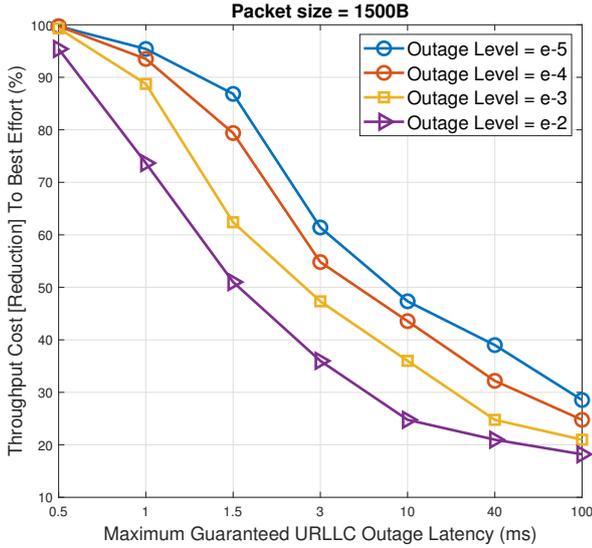


Figure 7. Spectral efficiency cost of achieving the URLLC outage targets, large payload size.

the URLLC service class, compared to the best effort case. We consider various outage levels and latency budgets of the large and small payload URLLC cases, respectively. In particular, such cost denotes how much network throughput is lost (paid), relative to the best effort case, in order to fulfill the corresponding stringent URLLC outage latency target. For example, with the large-payload URLLC case in Fig. 7, the throughput cost spans the range from 20% up to 97%. To fulfill a maximum guarantee latency of 0.5 ms while employing the URLLC large payload, the supported network offered load is 97% less than that is of the best effort case. This is majorly because, with the large payload URLLC transmissions, and to fulfill such stringent latency deadline, URLLC packets must be scheduled within a single TTI duration, and without further packet queuing or re-transmissions. Therefore, a single large-payload URLLC packet scheduling consumes the entire bandwidth, i.e., the majority of the available PRBs. Hence, the maximum supported offered capacity is drastically reduced compared to the best effort case. Similar conclusions can be drawn from Fig. 8, for the case of the URLLC small payload size, i.e., 50 Bytes.

#### IV. ACKNOWLEDGMENTS

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#### V. CONCLUDING REMARKS

In this paper, a comprehensive analysis of the system capacity loss, due to satisfying the various URLLC targets, is presented by means of extensive system level simulations. The paper answers the following research question: "what is the network capacity loss, compared to best effort case, due to fulfilling a guaranteed maximum URLLC latency and reliability target?", and hence, the paper offers valuable insights for

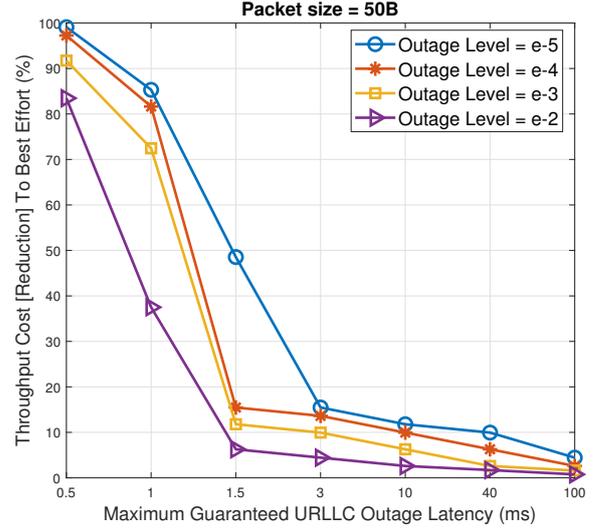


Figure 8. Spectral efficiency cost of achieving the URLLC outage targets, small payload size.

telecom operators to adapt their pricing models within their multi-QoS 5G deployments. Various URLLC configurations and settings are considered to match the different realistic URLLC use cases, and the achievable system capacity is compared to that is of the best-effort case, where the radio latency performance is relaxed.

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