Prioritized Service of URLLC Traffic in Industrial Deployments of 5G NR Systems*

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Abstract. The simultaneous support of enhanced mobile broadband (eMBB) and ultra-reliable low latency (URLLC) traffic types at the air interface in upcoming 5G New Radio systems is a challenging problem requiring new connection admission control and scheduling strategies. To enable this coexistence while still maintaining the prescribed quality-of-service guarantees the state of the art solutions utilize non-orthogonal multiple access and traffic isolation with explicit resource reservation. In this paper, we study an explicit prioritization of URLLC traffic over other services. Using the tools of queuing theory we mathematically characterize and investigate several techniques for priority-based resource allocation. Our results demonstrate that preemptive priority service is a viable option to fulfill strict delay and loss guarantees at the NR air interface. We also show that elasticity of lower priority eMBB service allows for additional capacity gains in terms of the eMBB session drop probability during the service.

Keywords: 5G · New Radio · Industrial NR · URLLC · Priority Service.

1 Introduction

In recent releases, 3GPP has specified three main types of services to be supported by 5G systems, enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low latency communication (URLLC). The former type is an enhancement of conventional mobility broadband service generated by existing and emerging applications requiring high rates at the access interface while the latter is a principally new one characterized by extreme reliability and latency requirements. While mMTC services addressed by technologies that are already available on the market (e.g., NB-IoT) eMBB

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and URLLC require innovations and expected to be supported by the developing NR technology.

Communication patterns in industrial environments can be characterized by two main attributes: periodicity and determinism [1]. Examples of a periodical transmission include updates of a position or the repeated monitoring of a characteristic parameter [2]. An aperiodic transmission is triggered instantaneously by an event, such events are defined by the control system (e.g., temperature or pressure threshold is exceeded) or by the user (e.g., remote diagnostic or maintenance events). Determinism refers to the latency of communication and jitter, which important for real-time services, such as closed-loop control or control-to-control communication. Actual manufacturing facilities commonly include all those communication patterns.

The resource demands of periodic communication sessions can be well addressed using static network planning methods, while aperiodic sessions may have high spatial and temporal variations, and thus less predictable. If the network planned based on the maximum demands possible in the covered area, the resource utilization of such network facilities would be low, while CAPEX and OPEX high. While reduced in the network capacity will compromise the reliability of communication. To reach a healthy balance between cost and reliability, a service model for different types of traffic is required for industrial deployments.

The high throughput requirements of URLLC traffic posse most sever demands for radio resource management subsystem [3, 4]. While the reliability requirements can be satisfied using conventional repetition coding benefiting from the large bandwidth at NR radio interface the latency requirement of just 1 ms one-day delay is much harder to satisfy. So far researchers have envisioned two approaches for support of URLLC traffic. These are non-orthogonal multiple access (NOMA, [5, 6]) and explicit resource reservation [7, 8]. The NOMA approach is based on the use of special codes allowing for simultaneous reception of intentionally overlapped transmissions. One of the major NOMA advantages is the capability of satisfying one-way delay constrain of 1 ms at the radio interface as URLLC transmission can be scheduled for transmission in the frame they were received. However, this approach has not been included in NR standards [9].

A case when URLLC services require high throughput is considered as the most challenging from the perspective of radio resource management [3, 4]. Resource reservation is a conventional approach for resource allocation for high and low priority traffic at the wireless interface. According to it, a certain fraction of resources can be exclusively assigned to URLLC traffic while the rest of the resources can be used for eMBB traffic. However, this approach is known to suffer from system severe resource under-utilization and/or potential loss of URLLC traffic as its arrival pattern may fluctuate in time [10]. The use of priority scheduling of resources efficiently alleviates these shortcomings by allowing URLLC and eMBB traffic to share the transmission resources. However, once the aggregated load exceeds the number of available resources eMBB sessions might be dropped. Thus, assessing eMBB traffic performance in the presence of high priority URLLC sessions is one of the open research problems.

In this paper, we study the priority-based resource allocation for URLLC traffic in the presence of elastic eMBB traffic of lower priority with minimum rate requirements. To this aim, we formulate the set of queuing theoretic models with different types of priority preemptive discipline with two arriving flows of constant bit rate and elastic nature, respectively. The metrics of interest are related to eMBB traffic performance in the presence of high priority URLLC traffic as well as overall system throughput.

The paper is organized as follows. The system model is formulated in Section 2. The queuing models capturing the service process of URLLC and eMBB traffic at NR BS are formulated in Section 3. Numerical results are provided in Section 4. The conclusions are drawn in the last section.

2 System Model

In this section, we introduce the system model by specifying its components including deployment and service models at the NR air interface. Finally, we specify metrics of interest.

2.1 Deployment and Air Interface

We consider a single NR BS serving two types of traffic: deterministic URLLC sessions and elastic eMBB sessions. Such a scenario may reflect the service process of e.g., remote monitoring sessions and direct communications between operational entities in the industrial environment as illustrated in Fig. 1. We specifically concentrate on the shortcomings and advantages of service disciplines at the air interface and abstract the wireless specifics by directly formalizing the service process of URLLC and eMBB types of traffic.

2.2 Traffic Types and Service Models

URLLC sessions are assumed to generate streaming traffic (e.g., maintenance messaging service between operational entities), which is characterized by extremely small randomly distributed service duration and first come, first served (FCFS) service discipline. eMBB service (e.g., remote monitoring) is assumed to be elastic in nature, i.e., can adapt to the changing network conditions by regulating the encoding rate at the sending side. Recall that usually, elastic traffic is parameterized by a certain file size to be transmitted and characterized by a variable service duration and processor sharing (PS) service discipline. In contrast, in our study eMBB sessions are still elastic but characterized by randomly distributed service duration that is independent of the network conditions over the lifetime of a session.

We now introduce the main notation utilized in this work, see Fig. 2. We consider a system operating using a channel with a raw rate of C bandwidth units (b.u.). URLLC and eMBB sessions arrive according to the Poisson process with rates λ_1 and λ_2 sessions per second, respectively (Fig. 2). The session

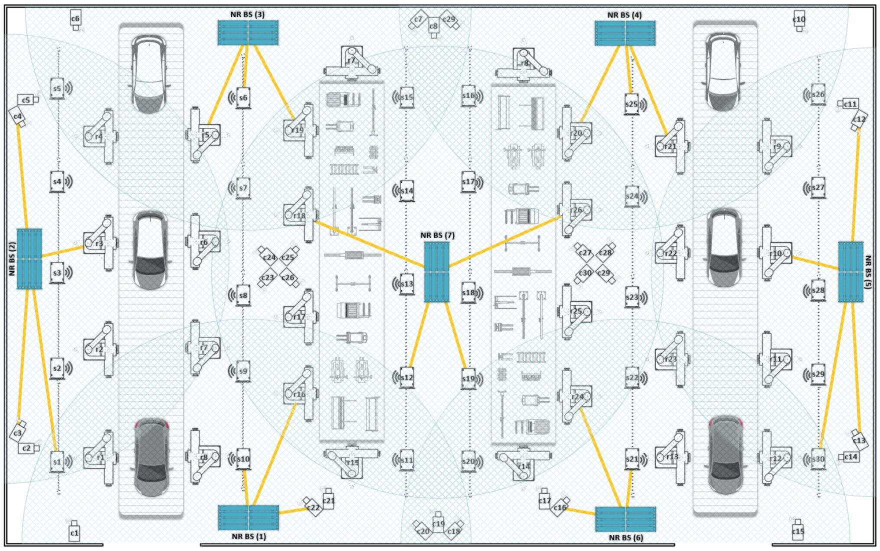


Fig. 1. Illustration of the service process.

service times are exponentially distributed with means μ_1^{-1} and μ_2^{-1} seconds, respectively. Since URLLC sessions correspond to streaming traffic, their resource requirements are guaranteed and equal to b_1 b.u., $b_1 \geq 1$. We consider two types of minimum allocations for eMBB traffic:

- **Strict strategy:** $b_2^{\min}$, $b_2^{\min} \geq 1$: in this case there is a single minimum threshold for eMBB sessions corresponding to the minimum monitoring session performance with satisfactory visual quality – if this threshold if violated the corresponding session is dropped during the service;
- **Flexible strategy:** $b_2^{\min_1}$ b.u., $b_2^{\min_1} \geq 1$: in this case there are two thresholds to protect eMBB sessions – if the amount of resources available for one or few eMBB sessions falls below the first threshold but remains above the second one, the session may still be served at reduced quality; the rationale is that URLLC sessions are extremely short-lived inducing just tiny load to the system implying that the resources available for eMBB sessions may recover.

Note that URLLC sessions are latency-sensitive, so we assume these are provided exclusive access to the transmission resources via preemptive-priority service discipline. This means that if there is a lack of system resources for a newly arriving URLLC session, the amount of resources allocated for the eMBB session can be reduced to the minimum requirement threshold $b_2^{\min_2}, b_2^{\min_1} > b_2^{\min_2} > 0$. If the amount of resources is still not sufficient to accept an arriving URLLC session one or more eMBB sessions can be interrupted. According to this service discipline, URLLC sessions can only be lost if their aggregated instantaneous load exceeds the system transmission resources.

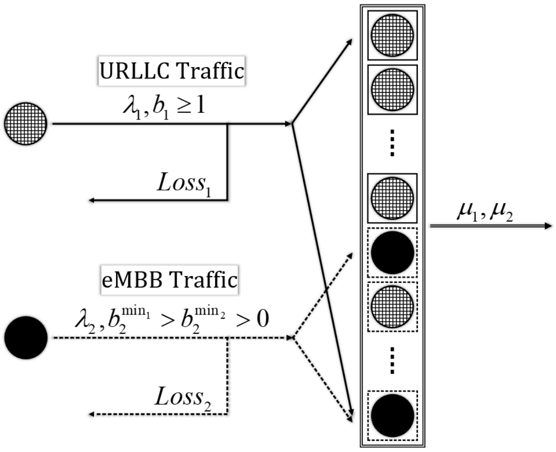


Fig. 2. Scheme model of the service process.

2.3 Parameterization and Metrics of Interest

To assess performance of the proposed service models in realistic environment one needs to provide the following metrics as a function of NR BS parameters, propagation characteristics and environment: (i) coverage of NR BS, (ii) mean resource request of URLLC and eMBB sessions. The former can be determined using the procedure offered in [11, 12] while the latter can be found as discussed in [13]. Note that we also do not explicitly specify the operational frequency of NR technology. In case of millimeter wave band one also needs to account for blockage phenomena using the models proposed in [14, 15].

In our study we concentrate on five main metrics of interest: (i) URLLC session drop probability, (ii) eMBB session drop probability, (iii) eMBB preemption probability (drop during the service), and (iv) resource utilization coefficient and (v) fraction of time eMBB session operates at reduced quality. These metrics are further utilized to make conclusions of the performance of the considered system.

3 Performance Evaluation Model

In this section we analyze the introduced system model for performance metrics of interest. We start with formalizing the model as a multi-dimensional Markov chain and then proceed characterizing its stationary state distribution and performance metrics of interest.

3.1 Model Formalization

The model with two resource requirements thresholds for eMBB sessions, $b_2^{\min_1}$ b.u., $b_2^{\min_1} \geq 1$, is a generalization of the one with a single threshold $b_2^{\min}$, $b_2^{\min} \geq 1$. Thus, we the consider the former case.

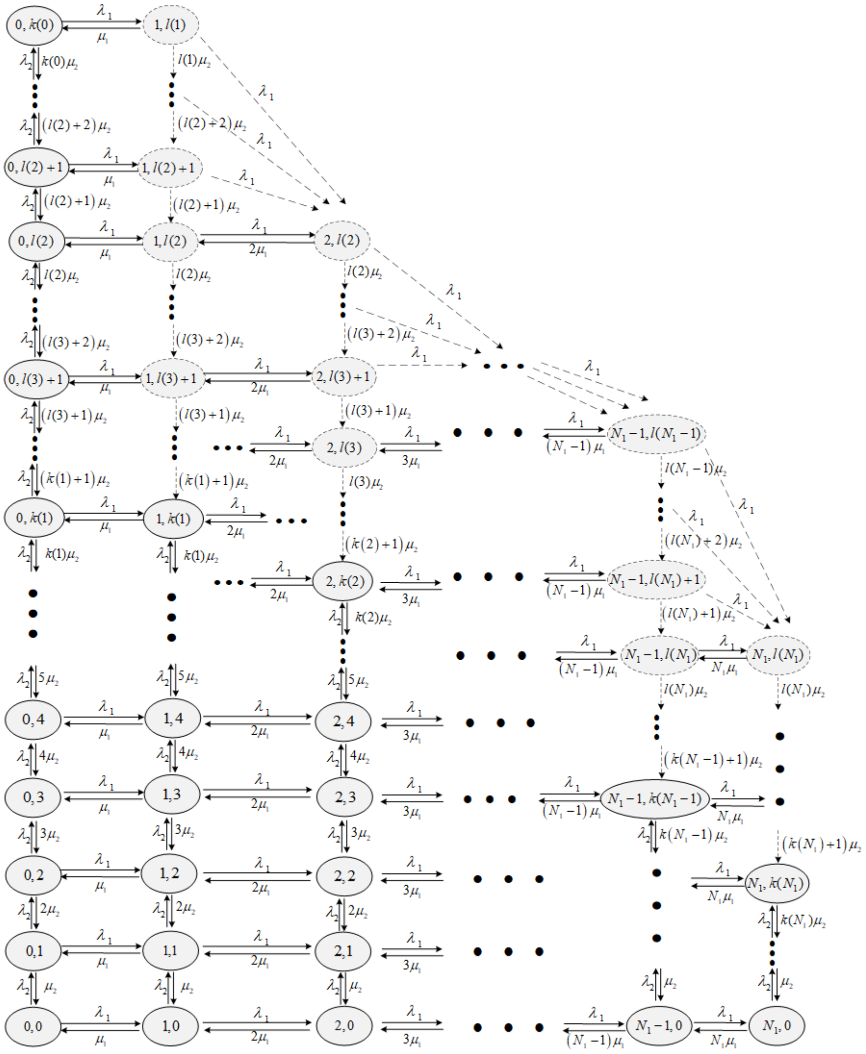


Fig. 3. The general view of the state transition diagram.

The behavior of the model can be described by a two-dimensional continuous-time Markov chain (CTMC) $\mathbf{X}(t) = N_1(t), N_2(t), t > 0$, where $N_1(t)$ is the number of URLLC sessions, $N_2(t)$ is the number of eMBB sessions at the time instant t. Taking into account that the arrival process is Poisson in nature while service times are exponentially distributed, the state space of the Markov model $\mathbf{X}(t)$ is provided by

$$\mathbf{X} = \left\{ (n_1, n_2) : n_1 = 0, .., \left\lfloor \frac{C}{b_1} \right\rfloor, n_2 = 0, .., \left\lfloor \frac{C}{b_2^{\min_1}} \right\rfloor, n_1 b_1 + n_2 b_2^{\min_2} \leq C \right\}, \quad (1)$$

where n_1 and n_2 are the number of URLLC and eMBB sessions in the system.

Introduce the following notations: (i) $N_1 = \lfloor C/b_1 \rfloor$ – the maximum number of URLLC sessions that can be simultaneously served, (ii) $N_2 = \lfloor C/b_2^{\min_1} \rfloor$ – the maximum number of eMBB sessions that can be simultaneously served, (iii) $k(n_1) = \lfloor (C - n_1 b_1)/b_2^{\min_1} \rfloor$ – the maximum number of eMBB sessions, which could be simultaneously served, if the current number of current URLLC sessions in the system isn_1, (iv) $l(n_1) = \min(N_2, \lfloor (C - n_1 b_1)/b_2^{\min_2} \rfloor)$ – the maximum number of eMBB sessions, that can be served occupying the minimum of $b_2^{\min_2}$ resources, if the current number of URLLC sessions in the system is n_1. Further, we note that due to the elastic nature of eMBB sessions, characterized by the uniform distribution of all system resources between all the simultaneously served eMBB sessions, an achievable amount of occupied resources $b_2(n_1, n_2)$ for this type of sessions depends on the state $(n_1, n_2) \in \mathbf{X}$ of the system,

$$b_2(n_1, n_2) = \left\lfloor \frac{C - n_1 b_1}{n_2} \right\rfloor. \tag{2}$$

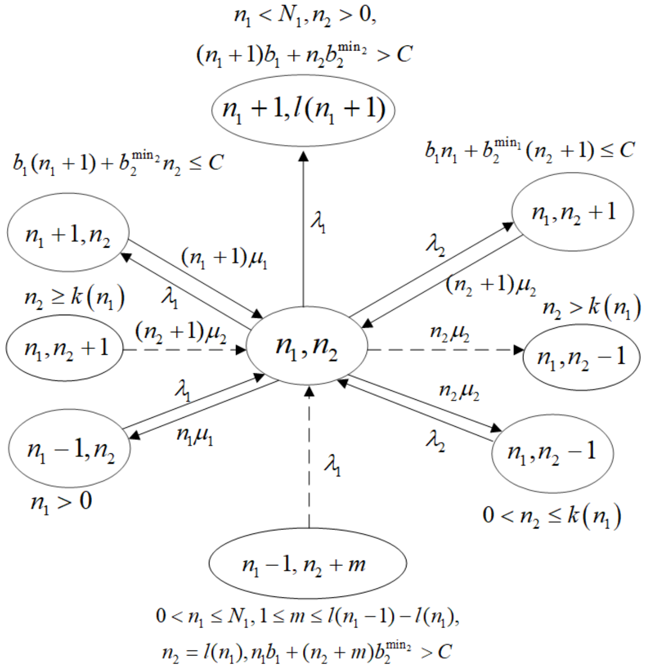


Fig. 4. Central state of the state transition diagram.

Further, we formalize the admission control mechanism, first, from the perspective of URLLC sessions, and, second, from the standpoint of the eMBB sessions. When a new URLLC session arrives, the following options are possible:

- if the system having free b.u. greater or equal to b_1, the URLLC session is accepted, the current number of eMBB sessions remains unchanged, and the amount occupied by eMBB sessions resources is higher than $b_2^{\min_1}$ b.u.;
- if the system having less than b_1 free b.u., the current number of served URLLC sessions is less than N_1, and the amount of occupied by eMBB sessions resources subject to the establishment of a new URLLC session is higher than $b_2^{\min_2}$ b.u., i.e. $b_2(n_1+1,n_2) \geq b_2^{\min_2}$, the URLLC session is accepted, and the amount of occupied resources by eMBB sessions is reduced to $\lfloor (C-(n_1+1)b_1)/n_2 \rfloor$ b.u., $b_2^{\min_2} \leq \lfloor (C-(n_1+1)b_1)/n_2 \rfloor < b_2^{\min_1}$;
- if the system having less than b_1 b.u. free, the current number of served URLLC sessions is less than N_1, the current number of served eMBB sessions are higher than 1, and the amount of occupied by eMBB sessions resources subject to the establishment of a new URLLC session is less than $b_2^{\min_2}$ b.u., i.e. $b_2(n_1+1,n_2) < b_2^{\min_2}$, the URLLC session is accepted and $\lfloor b_1/(b_2(n_1,n_2)) \rfloor$ served eMBB sessions will be preempted (dropped);
- otherwise the arrived URLLC session is dropped.

With the considered admission control rules, the overall structure of the state transition diagram of the CTMC is illustrated in Fig. 3, while Fig. 4 highlights the transitions associated with the central state of the model. With these admission rules, the central state of the system takes the form shown in Fig. 4.

Similarly, upon eMBB session arrive we have: (i) if the session finds the system having greater than or equal to $b_2^{\min_1}$ b.u. free the eMBB session is accepted, and (ii) otherwise the session is dropped. The associated equilibrium equations for $n_1 = 0,1,\ldots,N_1$, $n_2 = 0,1,\ldots,N_2$ are given by

$$\begin{aligned}
&(\lambda_1 I\{\mathrm{C}_1\} + n_1\mu_1 + \lambda_1 I\{\mathrm{C}_2\} + \lambda_2 I\{\mathrm{C}_3\} + n_2\mu_2)p(n_1,n_2) = \lambda_1 I\{\mathrm{C}_4\}\times \\
&\times p(n_1-1,n_2) + \lambda_2 I\{\mathrm{C}_5\}p(n_1,n_2-1) + (n_1+1)\mu_1 I\{\mathrm{C}_6\}p(n_1+1,n_2) + \\
&+ (n_2+1)\mu_2 I\{\mathrm{C}_7\}p(n_1,n_2+1) + \lambda_1 I\{\mathrm{C}_8\}p(n_1-1,n_2+m), \qquad (3)
\end{aligned}$$

where $\mathbf{p} = [p(n_1,n_2)]_{(n_1,n_2)\in\mathbf{X}}$ are the stationary state probabilities and

$$\begin{aligned}
&\mathrm{C}_1 \coloneqq n_1 < N_1, b_1(n_1+1) + b_2^{\min_2} n_2 \leq C,\\
&\mathrm{C}_2 \coloneqq n_1 < N_1, n_2 > 0, b_1(n_1+1) + b_2^{\min_2} n_2 > C,\\
&\mathrm{C}_3 \coloneqq n_2 < N_2, b_1 n_1 + b_2^{\min_1}(n_2+1) \leq C,\\
&\mathrm{C}_4 \coloneqq n_1 > 0, b_1 n_1 + b_2^{\min_2} n_2 \leq C,\\
&\mathrm{C}_5 \coloneqq n_2 > 0, b_1 n_1 + b_2^{\min_1} n_2 \leq C,\\
&\mathrm{C}_6 \coloneqq n_1 < N_1, b_1(n_1+1) + b_2^{\min_2} n_2 \leq C,\\
&\mathrm{C}_7 \coloneqq n_2 < N_2, b_1 n_1 + b_2^{\min_2}(n_2+1) \leq C,\\
&\mathrm{C}_8 \coloneqq 0 < n_1 \leq N_1, n_2 = l(n_1), n_2+m \leq N_2, b_1(n_1-1) + b_2^{\min_2}(n_2+m) \leq C,\\
&\quad b_1 n_1 + b_2^{\min_2}(n_2+m) > C. \qquad (4)
\end{aligned}$$

3.2 Solution Methodology

As a result of the preemptive-priority service mechanism, the CTMC $\mathbf{X}(t)$ is not a reversible Markov chain, so the stationary state probability distribution $p(n_1, n_2), (n_1, n_2) \in \mathbf{X}$ does not have product form. However, one can determine it numerically. For this purpose, we rewrite the system of equilibrium equations (3) as follows

$$\mathbf{pA} = \mathbf{0}, \mathbf{p1}^T = 1, \tag{5}$$

where $\mathbf{A}$ is the infinitesimal generator.

Having the stationary state probability distribution $p(n_1, n_2), (n_1, n_2) \in \mathbf{X}$, one can compute the performance measures of the considered system as follows:

- URLLC session drop probability B_1 is given by

$$B_1 = \sum_{i=0}^{l(N_1)} p(N_1, i). \tag{6}$$

- eMBB session drop probability B_2 is given by

$$B_2 = \sum_{i=0}^{N_1} \sum_{j=k(i)}^{l(i)} p(i, j). \tag{7}$$

- eMBB session preemption probability Π is given by

$$\Pi = \sum_{i=0}^{N_1-1} \sum_{j=l(i+1)+1, l(i)\neq l(i+1)}^{l(i)} \frac{\lambda_1 p(i, j)}{\lambda_1 + \lambda_2 I\{j < k(i)\} + i\mu_1 + j\mu_2}. \tag{8}$$

- mean resource utilization, U, is given by

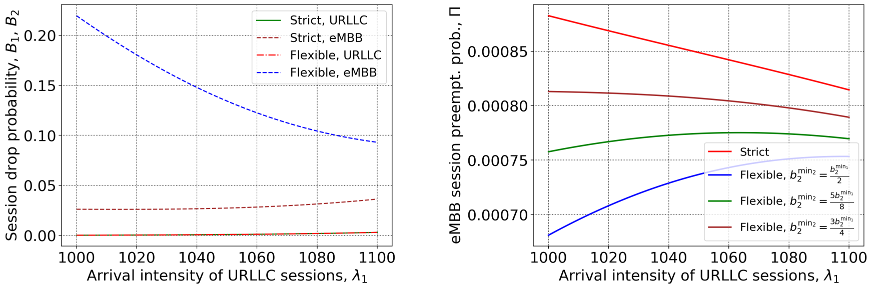
$$U = C \sum_{i=0}^{N_1} \sum_{j=1}^{l(i)} (i + j)p(i, j) + b_1 \sum_{i=1}^{N_1} ip(i, 0). \tag{9}$$

- fraction of time ω an arbitrary eMBB session is served with reduced quality is given by

$$\omega = \sum_{i=1}^{N_1} \sum_{j=k(i)+1, k(i)<l(i)}^{l(i)} jp(i, j) \Big/ \sum_{i=0}^{N_1} \sum_{j=0}^{l(i)} jp(i, j). \tag{10}$$

4 Numerical Results

In this section we elaborate on numerical results. We mainly concentrate on evaluating the use of preemptive-priority serving discipline for serving mixture of URLLC and eMBB traffic and comparing the proposed service schemes for eMBB traffic.



(a) Drop probability

(b) eMBB preemption probability

Fig. 5. Session drop and preemption probabilities.

The default system parameters are shown in Table 1. The coverage of NR BS is determined using the procedure offered in [11, 12] while the mean resource requests of URLLC and eMBB sessions are obtained found as discussed in [13]. To approximate URLLC traffic transmission latency, we set the associated mean service time to NR frame duration, 1 ms. To ensure reliable delivery of data within this deadline we assume repetition coding, i.e., the same replica of the URLLC message is repeated three times within the same NR frame.

Table 1. Parameters utilized for numerical assessment.

Parameter	**Value**
Carrier frequency	28 GHz
NR BS bandwidth	20 MHz
Transmit power	0.2 W
NR BS side antenna array	16x4
UE side antenna array	4x4
NR BS and UE heights	6 m, 1 m
Arrival intensity of URLLC sessions	1000 → 1100
Arrival intensity of eMBB sessions	2
Mean service time of URLLC sessions	0.1 s
Mean service time of eMBB sessions	120 s
Rate of URLLC sessions	0.8 Mbps
Minimum rate of eMBB sessions	10 Mbps

We start analyzing the system with Fig. 5 showing the session drop and preemption probabilities as a function of URLLC session arrival intensity. As one may notice, the URLLC session drop probabilities remain unchanged for both considered strategies. However, the considered strategies not only lead to drastically different absolute values of eMBB session drop probabilities but characterized by principally different qualitative behavior. The absolute values of these strategies coincide only when the URLLC arrival intensity increases. It is important that the flexible strategy leads to much higher eMBB session drop probabilities by it is compensated by significantly lower preemption probabilities.

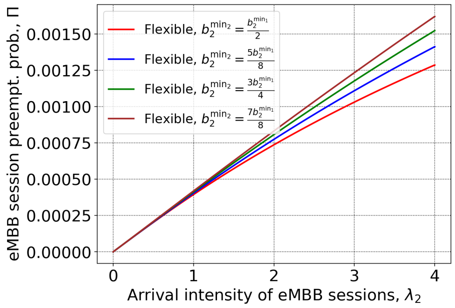


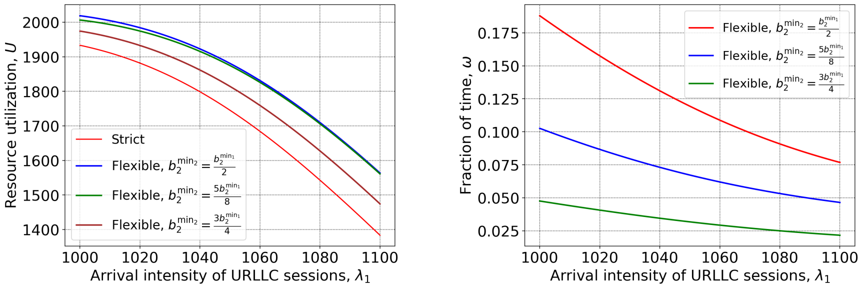
Fig. 6. Scheme model of the service process.

To complement the results illustrated in Fig. 5(b) we also demonstrate the dependence of eMBB session preemption probability on the arrival intensity of eMBB sessions in Fig. 6 for flexible strategy with different values of $b_2^{\min_2}$. As one may observe, contrarily to the effect of URLLC session arrival intensity, the difference induced by choosing $b_2^{\min_2}$ is negligible and the major effect is produced by the eMBB session arrival intensity.

Assessing the effect of considered strategies on the resource utilization shown in Fig. 7, we note that the flexible strategy allowing eMBB sessions to spend some time with degraded quality leads to much better usage across the whole range of considered URLLC arrival intensities. The price one has to pay for this gain is shown in Fig. 7(b) illustrating the fraction of time eMBB sessions served with degraded quality. We note that the usage of two limits of acceptable rates for eMBB sessions provides a simple and efficient method for network operators to balance QoS and resource utilization while maintaining absolute service priority for URLLC traffic.

5 Conclusions

In this paper, aiming to improve the resource utilization of NR BS serving a mixture of URLLC and eMBB traffic while still satisfying URLLC traffic delay constraints we developed the set of queuing-theoretic models with preemptive priority discipline. Assuming elastic eMBB sessions nature with two types of minimum guarantees we concentrated on the user- and system-level metrics of interest including system resource utilization, session drop probability for eMBB and URLLC services, and eMBB session preemption probability.



(a) Resource utilization (b) Fraction of time with reduced rate

Fig. 7. Resource utilization and fraction of time with reduced rate.

Our results indicate that compared to static resource reservation mechanism, priority-based service allows to reach $80 - 90\%$ of system resource utilization while still maintaining latency guarantees to URLLC sessions. On top of this, compared to dynamic resource reservation, the proposed resource allocation procedure does not require on-line resource reallocation procedures. The proposed service strategy can be utilized in those environments, where NR BS are expected to serve dynamically changing loads of URLLC and eMBB traffic, e.g., autonomous factories.

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