Reliability Enhancement of URLLC Traffic in 5G Cellular Networks

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Abstract. 5G cellular networks must be able to deliver a small data payload in a very short time (up to 1 ms) with ultra-high probability of success (99.999%) to the mobile user. Achieving ultra-reliable and low-latency communication (URLLC) represents one of the major challenges in terms of system design. This paper covers definitions of latency and the reliability of URLLC traffic. Furthermore, it presents a method for reliability enhancement of URLLC traffic. To this end, the problem of reliability enhancement is formulated as an optimisation problem, the objective of which is to maximise the sum of data rates for all users with the URLLC constraints. Simulation results show that the suggested method validates the proposed model.

Keywords: 5G systems · Wireless scheduling · URLLC traffic · eMBB traffic · Reliability

1 Introduction

The newly introduced fifth generation (5G) mobile cellular network is the first wireless network standard designed to support multi-service communication [1]. More specifically, 5G aims to cover three generic connectivity types: enhanced Mobile Broadband (eMBB), massive Machine-Type Communication (mMTC) and Ultra-Reliable Low-Latency Communication (URLLC). eMBB is an enhancement of the mobile broadband services of the current long term evolution (LTE) system. mMTC service provides massive connectivity solutions for various Internet of Things (IoT) applications. The main design goals are supporting high density of devices (up to a million devices per square kilometer) and significant extension of the lifetime of individual devices (up to 10 years battery lifetime) [2]. Ultra-Reliability Low-Latency Communication (URLLC) supports low latency transmissions (0.25–0.3 ms/packet) with high reliability (99.999%) [3]. Satisfying these very high requirements makes 5G network implementation a major design challenge.

In general, in 5th generation networks, the problem of three traffics can be treated by two approaches. The first approach involves analyzing orthogonal slicing. Then all different slices are allocated to all three types of traffics.

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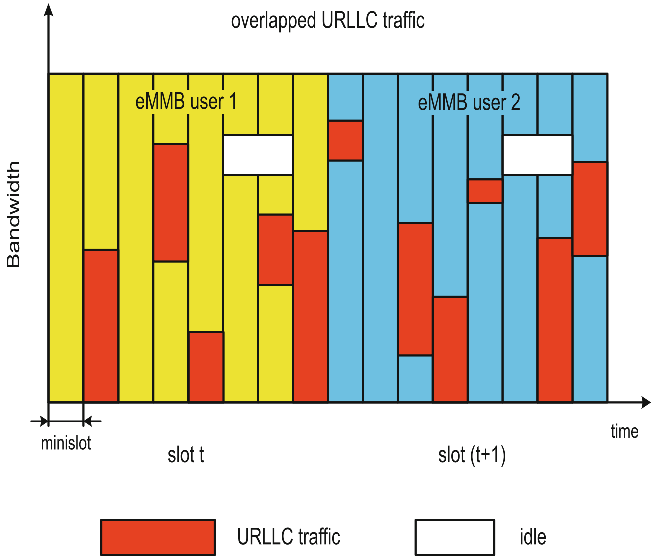

Fig. 1. Superposition approach for multiplexing eMMB and URLLC in 5G cellular network.

Then there is no interference between these traffics. This approach is characterized by inefficiency in the use of resources. It was analyzed, among others in papers [4–6]. Unlike previously described, the second approach does not require orthogonal slicing. The use of non-orthogonal slicing allows you to increase resource efficiency, but can cause interference between these traffics. This approach was used, among others, in [7–9].

This work considers non-orthogonal slicing for downlink resource allocation of URLLC and eMBB. The third type (mMTTC) support a large number of things (IoT) devices and can be used sporadically, so this will not be considered here either. In this work it was assumed that each time slot is divided into 0.125 ms minislots [2,10]. As can be seen in Fig. 1, this describes this structure, within each slot, eMBB traffic can share the bandwidth over the time-frequency plane. Time is divided into slots, and further is also divided into minislots. eMBB traffic is located at the beginning of the slots, while URLLC traffic can be overlapped at any minislot. A number of users are flexibly multiplexed over the available resources with different transmission time interval (TTI) durations. The TTI size can be dynamically adjusted according to the number of users, their requirements, etc. A long TTI allows us to take advantage of the benefits of coding gains closer to the Shannon capacity limit, and also imposes a lower control overhead. Unfortunately, this can cause an increase in latency. Hence, it is obvious that a proper scheduling of users can minimise the latency and reliability requirements.

Message transmission for mission-critical applications needs a latency of not more than a few milliseconds or even lower than 1 ms for fully autonomous applications [11]. It is not possible to use the LTE system here, because it provides a delay of 30 to 100 ms and this is unacceptable. The opposite is provided by a special URLLC service described a.o. by P. Schulz, *et al.* [12]. To achieve this, the grant-free transmission mechanism of the physical layer access was proposed by C. She *et al.* [13]. The appropriate modulation schemes and the number of links are proposed as a solution to this problem by W. Anwar *et al.* [14]. In turn, the multi-connectivity activation scheme for URLLC constraints as a new approach in their implementation was proposed by J. Rao *et al.* [15].

In this paper, the problem of reliability enhancement in the finite blocklength regime subject in URLLC traffic is discussed. Through the optimisation of the data rate, with the reliability constraints it is possible to obtain all the required parameters of the URLLC downlink packets arriving during an eMBB transmission. This allows us to find a solution that is different from those obtained by minimising just the mean resource utilisation. In addition, the contribution of this article is the development of a new online approximated algorithm that allows you to increase the reliability of URLLC traffic regardless of the load.

The remaining parts of this paper are as follows. Section 2 presents the system model. In this section the problem of the reliability enhancement is formulated as an optimisation problem with reliability constraints and transformed into deterministic form. Section 3 presents the optimal resource allocation problem. In Sect. 4, the online heuristic algorithm for reliability enhancement of URLLC traffic is provided. Simulation results are then presented in Sect. 5, followed by concluding remarks in Sect. 6.

2 System Model

2.1 Traffic Model

In this model, the time is divided into equally spaced slots with one millisecond time duration, which is compatible with current cellular network solutions. The downlink eMBB traffic originating from the backlogged users shares the bandwith over the time frequency plane in each slot and is fixed during that slot. The downlink stochastic URLLC traffic may arrive during the time slot which is allocated to different eMBB users. The URLLC traffic cannot be queued until the next slot. Therefore, each eMBB slot is divided into minislots, each of which has a 0.125 ms duration. This means that each arrived URLLC traffic is scheduled immediately in the next minislot on top of the ongoing eMBB transmission (see Fig. 1).

2.2 The Reliability Requirements of URLLC Traffic

The system bandwidth W is chosen that the probability of blocking of a URLLC packet arrival is of the order of δ. The QoS parameters of URLLC traffic d and δ

are specified as follows: a packet must be successfully delivered within a end-to-end delay of no more than d seconds with a probability of at least $1 - \delta$. Thus, δ means here the reliability of the URLLC traffic. Let λ be the system load and $\mathbf{r} = (r_1, r_2, \ldots, r_C)$ be a number of channels, where C is total number of classes. Each class represents users with the same SINR. Let the set of all classes be given as $\mathcal{C}$. Thus, the following condition must be satisfied, namely [16,17]:

$$W \geq \zeta^{mean}(\mathbf{r}) + c(\delta)\sqrt{\zeta^{variance}(\mathbf{r})} \tag{1}$$

where $c(\delta) = Q^{-1}(\delta)$, $Q(.)$ is the Q-function, $\zeta^{mean}(\mathbf{r}) = \sum_{c=1}^{C} \lambda_c \frac{r_c}{\kappa}$ is the mean bandwith utilisation and $\zeta^{variance}(\mathbf{r}) = \sum_{c=1}^{C} \frac{r_c^2}{\kappa^2 d}$ is the variance of the bandwith utilisation, κ is the a constant which denotes the number of channel uses per unit time per unit bandwidth of the OFDMA time-frequency plane.

2.3 Joint eMBB/URLLC Scheduling in One Slot

The scheduling combines two movements dependent on the eMBB state and the URLLC traffic, which is a strategy for placement across minislots. This strategy takes into account the eMBB users, and in turn the URLLC must be located so that their requests or blocking are included. Therefore, to carry out this scheduling, the URLLC traffic data should be allocated in each minislot, if one is required. This is done by affecting the data rate of eMBB traffic. Thus, the data rate of the m-th eMBB user is given as follows:

$$R_{eMBB}^{m} = \sum_{i=1}^{N} (b_i - f_{m,i}) \log_2(1 + SINR_i) \tag{2}$$

where b_i is the resource allocated to URLLC user i, $f_{m,i}$ is the busy resource of eMBB m-th user by the URLLC data, $SINR_i$ is the signal-to-noise ratio of i-th URLLC user, N is the total number of URLLC user.

The data rate of the i-th URLLC user on subcarrier k is given by

$$R_{URRLC}^{i} = \log_2(1 + p_{i,k}\gamma_{i,k}) \tag{3}$$

where $p_{i,k}$ is the transmission power to the i-th URLLC user on the subcarrier k, $\gamma_{i,k} = h_{i,k}/(N_0 W + I_{i,k})$ is the signal to interference plus noise ratio (SINR), $h_{i,k}$ is the channel gain on subcarrier k and the i-th URLLC, N_0 is the noise power and $I_{i,k}$ is the interference introduced to the i-th URLLC user on the subcarrier k.

The total data rate in a downlink transmission is given by

$$R = \sum_{m=1}^{M} R_{eMMB}^{m} + \sum_{i=1}^{N} R_{URLLC}^{i} = \frac{W}{\Theta} \sum_{j=1}^{M+N} \sum_{i=1}^{\Theta} \log_2(1 + \frac{\gamma_{j,i}}{\Gamma}) \tag{4}$$

where Γ is a function of the required bit-error rate (BER) and is approximately equal $\Gamma \triangleq -\ln(5BER)$ [18]. In the range of BER $< (\frac{1}{5})\exp(-1.5) \approx 0.0446$. Θ is the number of orthogonal subbands.

3 Optimal Resource Allocation

This section presents the problem of optimal resource allocation of the URLL data in the eMBB data traffic with the reliability enhancement.

According to Eq. (2), the achievable eMBB data rate at each time T is given by

$$\max \sum_{t=1}^{T} \sum_{i=1}^{N} \sum_{m=1}^{M} w_{i,m}^{(t)} R_{eMMB}^{(m,t)} \tag{5}$$

subject to:

$$C1: \quad R_{eMBB}^{(m,t)} \geq R_{eMBB}^{req}, \quad \forall m \in \mathcal{M}, \quad \forall t \in \{1, \ldots, T\} \tag{6}$$

$$C2: \quad \sum_{r \in \mathcal{C}} \left(\sum_{m \in \mathcal{M}} R_{eMBB}^{(m,t)} x_{m,r}^{(t)} + \sum_{i \in \mathcal{N}} R_{URLLC}^{(i,t)} x_{i,r}^{(t)} \right) \leq R, \quad x_{m,r}^{(t)} \in \{0,1\},$$

$$x_{i,r}^{(t)} \in \{0,1\}. \;\; \forall r \in \{r_1, r_2, \ldots, r_C\}, t \in \{1, \ldots, T\} \tag{7}$$

$$C3: \quad x_{m,r}^{(t)} + x_{i,r}^{(t)} \leq 1, \;\; x_{m,r}^{(t)} \in \{0,1\}, \;\; x_{i,r}^{(t)} \in \{0,1\}, \;\; m \in \mathcal{M}, \;\; i \in \mathcal{N},$$
$$\forall r \in \{r_1, r_2, \ldots, r_C\}, \quad t \in \{1, \ldots, T\} \tag{8}$$

$$C4: \quad R_{URLLC}^{(i,t)} \leq R_{URLLC}^{res}, \quad \forall i \in \mathcal{N}, \quad \forall t \in \{1, \ldots, T\} \tag{9}$$

where the $C1$ condition represents a limitation of required data rate for each m-th eMBB traffic user in slot t; the $C2$ condition is a limitation of the system data rate for all M eMBB traffic users and N URLLC users in the slot t. Equation $C3$ ensure that the r-th channel will be utilised in the slot t. The $C4$ condition represents the data rate restriction that can be used by i-th URLLC traffic user in the slot t. $w_{i,m}^{(t)}$ is the weight in the t-th slot for m-th eMBB user and i-th URLLC traffic user in the slot t. $x_{m,r}^{(t)}$ denotes the traffic indicator, i.e. $x_{m,r}^{(t)} = 1$ only if the m-th eMBB traffic is allocated to the r-th channel and $x_{m,r}(t) = 0$ in the slot t otherwise. Similarly, $x_{i,r}^{(t)} = 1$ indicated that the r-th channel is assigned to the i-th URLLC user in the slot t and $x_{n,r}^{(t)} = 0$ otherwise.

The optimisation problem is stochastic, nonlinear, non-convex and includes three variables, namely binary $x_{m,r}^{(t)}$, $x_{i,r}^{(t)}$ and $w_{i,m}^{(t)}$. So, the problem giving in Eq. (5) is a Stochastic Mixed Integer Programming (SIMP) [19]. There are two elements to this modelling, namely: Stochastic Programming (SP) and Mixed-Integer Programming (MIP). Each element is important to capturing the different factors involved in the problem. The computational complexity of finding the exact solution is very high thus not reasonable in practice. The alternative is to use heuristic approaches. In Sect. 4, a novel polynomial time heuristic algorithm for the suboptimal traffic scheduling for reliability enhancement is proposed.

4 Online Heuristic Algorithm for Reliability Enhancement of URLLC Traffic

The proposed online heuristic algorithm is based on sliding windows model [20]. This model allows to perform the required computations using the stream generated by a single scan of the data. This dynamic approach provides less precise statements than the static one since it uses less information and it has higher implementation overhead. However, this model allows progressive creation of the planning sequence.

Each scheduling period in the presented model corresponds here to the assumed window length, which is the slot time. Packets belonging to the both traffics, namely eMBB and URLLC, are scheduled in this window. These packets in the t-th scheduling period form a set, namely: $\{SP\}_t = \{packet_{t,1}, \ldots, packet_{t,J}\}$, where J is the total number of packets in time slot. The packet scheduling is based on the arrival time, the required end-to-end delay, the reliability, the waiting time, and the packet usability. All of the packet parameters listed above have been standardised according to the following relationship:

$$f(y_k) = \frac{y_k - \min_{packet \in \{SP\}_t}(y_k) + 1}{\max_{packet \in \{SP\}_t}(y_k) - \min_{packet \in \{SP\}_t}(y_k) + 1} \tag{10}$$

Four priorities have been calculated for such standardised parameters. So, priority of the time arrival for j-th packet is given by

$$A_j = \frac{AP_j}{UP_j} \tag{11}$$

where AP_j is the standarised time arrival of packet j and UP_j is the standarised usability of packet j. The priority of the required end-to-end delay for the packet j is as follows

$$D_j = \frac{DP_j}{UP_j} \tag{12}$$

where DP_j is the standarised end-to-end delay of packet j. The priority of the reliability for j-th packet is defined as follows

$$R_j = \frac{RP_j}{UP_j} \tag{13}$$

where RP_j is the standarised reliability of packet j. The usability of the packet j is given by

$$U_j = \frac{UP_j}{TT_j} \tag{14}$$

where TT_j is type of traffic to which j-th packet belongs. It is assumed here that the parameter $TT = 1$ and $TT = 2$ for eMBB traffic and URLLC traffic, respectively.

In addition, to avoid possible conflicts between packages, resulting from, among others due to lack of space in the mini-slot, a conflict index γ is entered for each packet j. It is defined as the number of packets in conflict with the j-th packet. Then for each packet j can be specified the degree of conflict DC_j as follows:

$$DC_j = \frac{Z_j}{(1+\gamma_j)^2} \tag{15}$$

where Z_j is the number of packets that are observed by the packet j and are in potential conflict with packet j. If the DC_j value is greater than the set value, the packet j is suspended and placed at the beginning of a new slot.

The concept of the heuristic algorithm is as follows:

1) The number of packets that can be placed in a single window is found initially. Packets from the buffer that are not included in the previous window are attached to these packets. For each packet separately all parameters are calculated, namely: A_j, D_j, R_j, U_j.
2) A value DC_j is also calculated for each packet to be placed in a single window. If the DC_j value exceeds the set bound, then the j-th packet with this value is removed from the list of packets to be placed in the window. This packet is placed in the packet buffer, which will be placed in the next window.
4) Parameters such as W, R_{eMBB}, ρ, δ are calculated for the entire list of packets to be placed in the window. If these parameters are not satisfied, all holes in the minislots are filled with packets from the buffer.
5) If the entire contents of the list of packets found for the window is accepted, then all of them are accepted for transmission in the window.

The pseudocode of the algorithm for placing packets in the sliding window is represented by Algorithm 1. It consists of two procedures: *Sliding window* and *Heuristic*. The first one prepares a list of $\{SP\}$ packets for each window t, for which all necessary parameters are calculated. Then sorts them by priority. All sorted packets are placed in the $\{SP\}$ list, which contains packets to be placed in the window. But before their final acceptance, the *Heuristic* procedure is called. Its purpose is to check the degree of possible conflicts. If their values are too high, it removes the packet from the $\{SP\}$ list and places it in the buffer. Then, until the performance parameters (W, R_{eMBB}, ρ, δ) for this scheduling are met, it will check for any free spaces in each minislot l. If he finds them, he fills them with packets from the buffer. Packets that meet all requirements are sent in the window by *Send_to_transmission* procedure.

The proposed algorithm has the complexity of $O(J^2)$ per slot, where J is the total number of packets per slot and scheduled in a single window (Table 1).

Algorithm 1. Heuristic online algorithm for reliability enhancement

procedure Sliding window
Require: $\{buffer\}, \{SP\}, \{Final\_SP\}$
Initialisation:
  Let $t \leftarrow 1$;
  Let $\{buffer\} \leftarrow \varnothing$;
  Let $\{SP\}_t \leftarrow \varnothing$;
  Let $\{Final\_SP\} \leftarrow \varnothing$;
  for $t \leftarrow 1, T$ **do**
    $j \leftarrow 1$
    if $\{buffer\} \neq \varnothing$ **then**
      Copy $\{buffer\}$ to $\{SP\}_t$
      $\{buffer\} \leftarrow \varnothing$
    end if
    repeat
      Add $packet_j$ to $\{SP\}_t$
      Calculate $A_j, D_j, R_j, U_j, \gamma_j$
    until $j > J$
    Sort all packets in $\{SP\}_t$
    Heuristic($\{SP\}_t$, $\{Final\_SP\}$)
    Send_to_transmission($\{Final\_SP\}$)
    $\{SP\}_t \leftarrow \varnothing$
    $\{Final\_SP\} \leftarrow \varnothing$
  end for
end procedure

procedure Heuristic($\{SP_t\}, \{Final\_SP\}$)
Require: $minislot[L]$
  while $\{SP\} \neq \varnothing$ **do**
    repeat
      Calculate DC_j
      if $DC_j > Limit$ **then**
        Copy $packet_j$ to $buffer$
      end if
    until $j > J$
    while $(W_J < W_{req}$ or $R^J_{eMBB} \geq R^{req}_{eMBB}$ or $\delta < \delta^{req}$ or $\rho < \rho^{req})$ **do**
      $l \leftarrow 1$
      repeat
        Find free holes in $minislot_l$
        Copy packets from the $buffer$ to $minislot_l$
      until $l > L$
    end while
    Copy $\{SP\}_t$ to $\{Final\_SP\}$
  end while
end procedure

Table 1. Main parameters of simulation

Parameter	Value
Source image size	800×600
IFFT size	512
Number of OFDM subcarriers	256
OFDM symbol length [μs]	60
OFDM symbol number	4
Carrier frequenxy [MHz]	2000
Modulation method	QPSK
CRC Length [bits]	16
Propagation conditions	Log-Normal shadowing with 5 dB standard deviation; $128.1 + 37.6 \log(D[km])$
Signal-to-Noise Ratio (SNR) Transmission bandwith	5 dB 20 MHz
Network environment	17 picocells
Traffic elements	URLLC 10 users/cell; eMBB 10 users/cell

5 Simulation Results

In this section, the results of simulations of the proposed resource allocation scheme for reliability enhancement are presented. The simulation environment comprises a multicell 5G network constructed according to the network model in Sect. 3, where multiple picocells share the spectrum resources with one macrocell and a variable number of D2D connections.

Firstly, the scheduling to ensure eMBB throughput was checked. It has been assumed that 10 eMBB users per picocell are active in the system. The eMBB slot of each of these users is composed of eight minislots. For seven eMBB users, the probability of distribution was chosen so that the average rate is equal 5 Mbps, and for the other three probability distribution is such that the average rate is 3 Mbps. The number of listed states here is around 1 million. URLLC traffic is scheduled in minislots so that peak URLLC load in an eMBB slot is less than or equal to $1 - \delta$.

Figure 2 shows the average rate of both traffics versus the average rate of URLLC load for two scheduling policies: the proportional-fair sharing algorithm [21] for eMBB users and the heuristic online algorithm. The graph shows that the system with the heuristic algorithm is characterised by a greater average data rate than the standard eMBB algorithm. This is especially evident in the case of high average URLLC load.

Then the system reliability obtained was tested. Figure 3 presents the sum data rates of eMBB users versus the reliability levels of URLLC traffic for both scheduling policies. The figure shows that the use of the heuristic online algorithm provides a higher sum of data rate for eMBB, which means that this algorithm improves data flow at the same URLLC reliability levels.

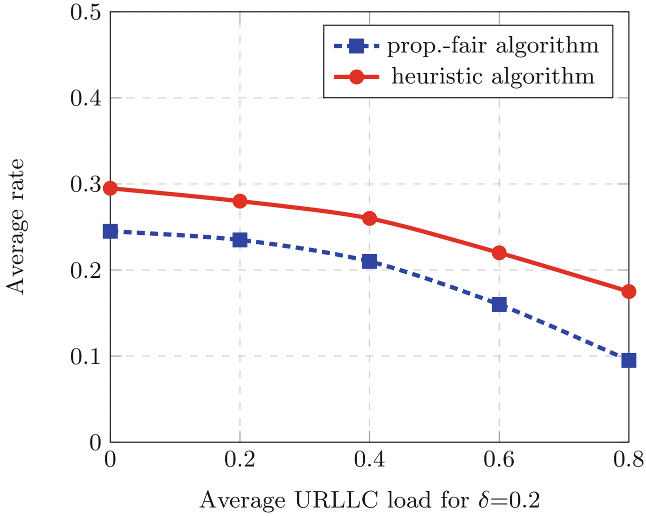

Fig. 2. Average rate of eMBB and URLLC traffic versus average URLLC load for the proportional-fair sharing algorithm and the heuristic online algorithm.

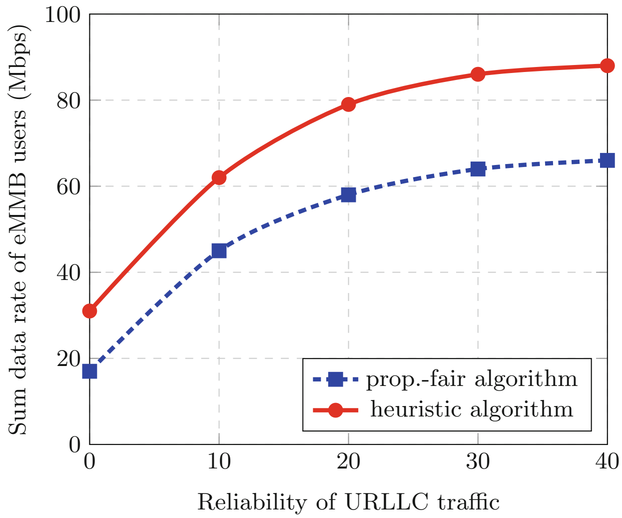

Fig. 3. Sum data rates of eMBB users versus the reliability levels of URLLC traffic for the proportional-fair sharing algorithm and the heuristic online algorithm.

Finally, the reliability levels at 1 ms latency for different URLLC loads was studied for both scheduling policies. Figure 4 shows the reliability at 1 ms latency versus different URLLC loads for both scheduling policies. It can be seen from the figure that the use of the proposed scheduling algorithm allows reliability to be increased by approx. 15–20%, regardless of the URLLC traffic load.

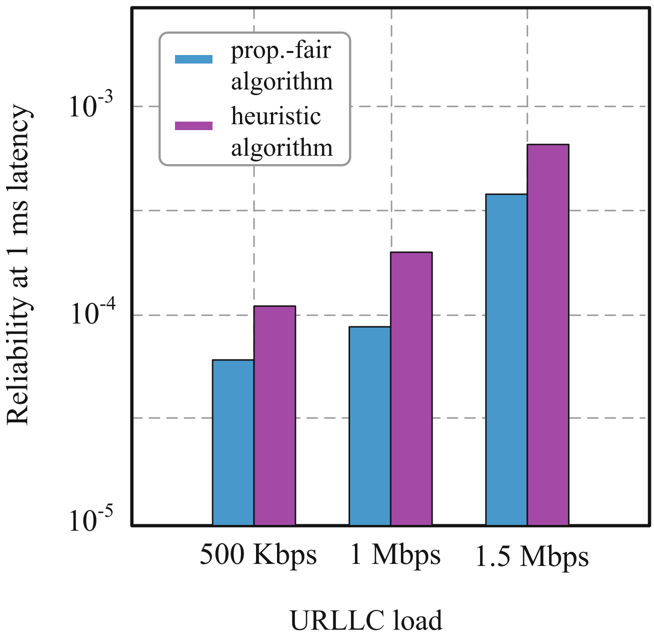

Fig. 4. The reliability at 1 ms latency versus average load of URLLC for the proportional-fair sharing algorithm and the heuristic online algorithm.

6 Conclusion

In this paper, the problem of reliability enhancement in the 5G cellular network was studied. An optimal resource allocation policy is proposed to maximise the reliability. Via simulation, the achievable reliability of the network with the proposed resource allocation policy was used. In particular, the achievable reliability obtained using standard methods was compared with the reliability obtained by applying the proposed solution of maximising the reliability in the studied model. Significant performance differences between these reliabilities are observed, which confirm the necessity and contribution of this paper.

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