Research Article

RB Allocation Scheme for eMBB and URLLC Coexistence in 5G and Beyond

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In this paper, we studied resource allocation in a dynamic multiplexing scenario of two 5G services, namely, enhanced mobile broadband (eMBB) and ultrareliable low-latency communication (URLLC). Considering that eMBB services focus on high data rates while URLLC is very strict in terms of latency and reliability, we formulate a joint eMBB/URLLC resource allocation problem. To solve the formulated problem, in particular, we propose a joint resource allocation algorithm that can satisfy both eMBB user rate and URLLC interrupt probability requirements. We propose an RB allocation scheme that takes into account the needs of eMBB and URLLC users. The program consists of two phases as follows: (1) establish an RB allocation for eMBB users and (2) assign the minislot for URLLC users and calculate the transmission power of URLLC users that ensures the reliability constraint. We also realize and verify the algorithm through the simulation.

1. Introduction

The services are supported by the 5th-generation (5G) new radio (NR) fall under three main application scenarios: enhanced mobile broadband (eMBB), ultrareliable low-latency communications (URLLC), and massive machine-type communications (mMTC) [1]. eMBB is designed to accommodate high data rate applications such as 4K video and virtual reality (VR), which creates the ultimate communication experience for users. URLLC mainly covers autonomous vehicles, industrial automation, tactile Internet, or remote surgery and other services, providing users with millisecond level end-to-end delay and a nearly 100% business reliability guarantee [2]. mMTC mainly aims at large-scale machine communication scenarios in the Internet of Things. A large number of mMTC devices may connect to a base station (BS), making it infeasible to allocate a priori resources to each device. Generally, mMTC devices, such as sensing, metering, and monitoring, focus on energy efficiency. In these three kinds of application scenarios, the research on 5G NR is aimed at meeting the great challenge of diversified

differentiated services after 2020 and multidimensional capability indexes such as ultrahigh rate, ultralow delay, high-speed movement, high energy efficiency, and ultrahigh traffic and connection density.

An important goal of 5G NR evolution is to make the service models of three different application scenarios effectively reusable for the same frequency band. From the perspective of a 5G wireless network evolution strategy, nb-iot/EMTC serves as the main bearing network of mMTC, and a small number of new mMTC services are from a 5G NR bearer. Generally, the ability to efficiently support both broadband and ultralow latency reliable communications is the most important requirement of the 5G wireless system [3, 4]. This paper focuses on the multiple reuse scenarios of the eMBB service and the URLLC service as well as the efficient coexistence scheme on the same carrier frequency.

To satisfy these heterogeneous requirements, the 3GPP standard body has proposed an innovative superposition/puncturing framework for multiplexing URLLC and eMBB traffic in 5G cellular systems [5].

In 5G NR, a frame consists of 10 subframes with lengths of 10 ms, and each subframe duration is fixed to 1 ms. As described above, in 5G/NR, multiple numerologies are supported, so the number of slots within one subframe is different with different numerology compared with 4G [6]. “Scalable subcarrier spacing” and the number of symbols within a slot do not change with the numerology, only with slot configuration type. Table 1 lists the 5G NR’s numerology-slot configurations. For example, for slot configuration 0, in a normal CP, with a numerology = 0 configuration, a subframe has only one slot in it, meaning a radio frame contains 10 slots in it. The number of OFDM symbols within a slot is 14. In a normal CP, with a numerology = 2 configuration, a subframe has 4 slots in it, meaning a radio frame contains 40 slots. The number of OFDM symbols within a slot is 14. For slot configuration 1, the number of symbols for a slot is always 7, as Table 1 describes.

Regardless of numerology, the length of one radio frame and the length of one subframe are the same. The length of a radio frame is always 10 ms, and the length of a subframe is always 1 ms.

Consider the downlink transmission scheme in 5G NR. The NR specifications offer a range of bandwidth (BW) and subcarrier spacing (SCS) configurations. The number of resource blocks (RBs) available for each of those configurations is shown in Table 2 (TS 38.101-1).

In general, a resource block (RB) is defined as 12 consecutive subcarriers in the frequency domain. Under different parameter configurations, the SCS is variable, but the number of subcarriers occupied by each RB is unchanged. For example, when the bandwidth is 50 MHz and the SCS is 15 KHz, the maximum number of RBs is 270, and the number of subcarriers in each RB is 12. When the bandwidth is 100 MHz and the SCS is 30 KHz, the corresponding maximum number of RB is 273, and the number of subcarriers per RB is still 12, but the actual bandwidth of each RB is doubled.

The 5G scheduling framework has the following structure [5]: at the beginning of each slot, the eMBB users share the RBs, which are fixed for the duration of a slot. URLLC downlink traffic may arrive during an ongoing eMBB transmission; they cannot be queued until the next slot in order to ensure the URLLC latency. The third-generation partnership project proposed the concept of short TTIs. 5G allows transfers for a part of the time slot, and each eMBB slot can be divided into minislots. A minislot is a URLLC transmission time interval (TTI). The shortest minislot only includes one OFDM symbol, and this kind of transmission mechanism can also be used to change the order of the data transmission queue. The arrival URLLC demand can be immediately scheduled in the next minislot on top of the ongoing EMBB transmissions to achieve very low latency. There are two approaches in the third-generation partnership project (3GPP) standard for the coexistence of URLLC and EMBB services. The first approach is superposition: the base station chooses nonzero transmission powers for both eMBB and URLLC users. The second approach is puncturing: eMBB transmissions are allocated zero power when URLLC traffic is overlapped in the minislot. This protocol

TABLE 1: Numerology-slot configuration (source: TS 38.211-Table 4.2.2-1).

μ	Slot configuration					
	N_{symb}^{μ}	0 $N_{\text{frame}}^{\text{slots}\mu}$	$N_{\text{sumframe}}^{\text{slots}\mu}$	N_{symb}^{μ}	1 $N_{\text{frame}}^{\text{slots}\mu}$	$N_{\text{sumframe}}^{\text{slots}\mu}$
0	14	10	1	7	20	2
1	14	20	2	7	40	4
2	14	40	4	7	80	8
3	14	80	8	—	—	—
4	14	160	16	—	—	—
5	14	320	32	—	—	—

is efficient in ensuring the URLLC latency but may impact eMBB transmission reliability.

Resource allocation issues for joint scheduling of URLLC and eMBB traffic have a major impact on cellular standards. We refer to [7, 8] for a survey of the issues. In this paper, we study the coexistence problem of eMBB and URLLC services in 5G NR and consider the puncturing approaches. We present the system model and problem formulation, propose an RB allocation scheme, and analyse the capacity of eMBB users while satisfying the URLLC users’ QoS constraints.

2. System Model

We consider a wireless system supporting eMBB users and URLLC traffic. There are different types of users connected to a gNB such as self-driving cars, smartphones, and industrial automation. eMBB scheduling decisions are made across slots while URLLC traffic arrives. The traffic then would be scheduled immediately across minislots. We consider a gNB serving K eMBB users and N URLLC users. Denote the EMBB set as $\mathcal{K} = \{1, \dots, K\}$ and the URLLC users set as $\mathcal{N} = \{1, \dots, N\}$. Let $\mathcal{B} = \{1, 2, \dots, B\}$ denote the total number of RBs, where each RB occupies 12 subcarriers in frequency.

2.1. eMBB Data Rate and Capacity. 3GPP release 15 has determined that OFDM is the basic modulation and demodulation technology with one RB. In general, an RB includes 12 consecutive subcarriers. We assumed that each user experiences independent fading in different RBs. We have denoted the channel gain of user k in RB b as g_{kb} , and additive white Gaussian noise (AWGN) is denoted as $\sigma^2 = N_0 B$, where N_0 is the noise power spectral density. The corresponding signal to noise ratio (SNR) of user k in RB b is denoted as $h_{kb} = g_{kb}/\sigma^2$, implying that the k th user’s received SNR on RB b is:

$$\gamma_{kb} = P_{kb} h_{kb}, \quad (1)$$

where P_{kb} is the downlink transmission power of the gNB on the RB b to user k .

In this paper, we consider the QoS requirements of eMBB users. When the M-QAM modulation is used and the error probability is measured in terms of the symbol

TABLE 2: Number of resource blocks for different configurations in NR (source: TS 38.101-1).

SCS (kHz)	5 MHz N_{RB}	10 MHz N_{RB}	15 MHz N_{RB}	20 MHz N_{RB}	25 MHz N_{RB}	30 MHz N_{RB}	40 MHz N_{RB}	50 MHz N_{RB}	60 MHz N_{RB}	80 MHz N_{RB}	90 MHz N_{RB}	100 MHz N_{RB}
15	25	52	79	106	133	160	216	270	N/A	N/A	N/A	N/A
30	11	24	38	51	65	78	106	133	162	217	245	273
60	N/A	11	18	24	31	38	51	65	79	107	121	135

error rate (SER), the number of bits per symbol R may be found as [9]:

$$r^{QoS} = \log_2 \left(1 + \frac{\gamma_{kb}}{\Gamma} \right), \quad (2)$$

where Γ is the SNR gap, which is defined as:

$$\Gamma = \frac{1}{3} \left[Q^{-1} \left(\frac{\text{SER}}{4} \right) \right]^2, \quad (3)$$

where the Q function is defined as $Q(x) = \int_x^\infty (e^{-u^2/2}/\sqrt{2\pi}) du$.

Accordingly, the data rate of an eMBB user k over an RB b at a time slot can be approximated as:

$$\begin{aligned} r_{kb} &= B \left(1 - \frac{\sum_{i=1}^M z_{ni}}{M} \right) r^{QoS} \\ &= B \left(1 - \frac{\sum_{i=1}^M z_{ni}}{M} \right) \log_2 \left(1 + \frac{P_{kb} h_{kb}}{\Gamma} \right), \end{aligned} \quad (4)$$

where z_{kb} is the number of the URLLC user punctured minislots from the RB b of eMBB user k at a time slot. B is the bandwidth of the RB b , and M is the total number of minislots in an eMBB time slot.

Therefore, from Equations (1), (2), and (4), we see that the data rate of the eMBB user k over all allocated RBs can be given as:

$$r_k = \sum_{b \in \mathcal{B}} x_{kb} B \left(1 - \frac{z_{kb}}{M} \right) \log_2 (1 + P_{kb} H_{kb}), \quad (5)$$

where $H_{kb} = h_{kb}/\Gamma$ is the effective channel SNR between both RBs and k th users and x_{kb} is the eMBB user scheduling indicator at the time slot, defined as follows:

$$x_{kb} = \begin{cases} 1, & \text{if the RB } b \text{ is allocated to user } k \text{ at the slot,} \\ 0, & \text{otherwise.} \end{cases} \quad (6)$$

Therefore, the ergodic capacity of the gBS for all the eMBB users in one time slot is then given by

$$C_{gBS} = E \left(\sum_{k=1}^K r_k \right), \quad (7)$$

where the expectation $E(\cdot)$ is taken over all the fading channels.

2.2. URLLC Data Rate and Reliability. For a URLLC user n puncturing the k th eMBB user transmission in a time slot, the achievable rate can be given as:

$$r_{nb} = B \frac{\sum_{i=1}^M z_{ni}}{M} \log_2 (1 + P_{nb} H_{nb}). \quad (8)$$

The SNR γ_{nb} of URLLC user n in RB b is given by $\gamma_{nb} = P_{nb} H_{nb}$.

The reliability of the URLLC is guaranteed through the probability of outage event, where its achievable rate, given below, is a predetermined threshold r_0 .

Define the probability of outage:

$$\Pr \{r_{nb} \leq r_0\} \leq p_0, \quad \forall n \in \mathcal{N}, \quad (9)$$

where p_0 is a small positive value ($p_0 < 1$).

2.3. Problem Formulation. We allocate RBs and transmission power to eMBB users at the beginning of each eMBB time slot. Then, we schedule the incoming URLLC traffic on the ongoing eMBB transmissions by puncturing some resources from eMBB users. Accordingly, the joint eMBB/URLLC resource allocation problem can be formulated as follows:

$$\max_{\{x_{kb}\} \{z_{kb}\} \{P_{kb}\}} C_{gBS}, \quad (10)$$

$$\text{s.t.} \Pr \{r_{nb} \leq r_0\} \leq p_0, \forall n \in \mathcal{N}, \forall b \in \mathcal{B}, \quad (10a)$$

$$0 \leq P_{kb} \leq P_{kb}^{\max}, \forall k \in \mathcal{N}, \forall b \in \mathcal{B}, \quad (10b)$$

$$0 \leq P_{nb} \leq P_{nb}^{\max}, \quad (10c)$$

$$r_i : r_j = \varphi_i : \varphi_j, \forall i, j \in \{1, \dots, K\} i \neq j, \quad (10d)$$

$$x_{kb} \in \{0, 1\}, \forall k \in \mathcal{N}, \forall b \in \mathcal{B}, \quad (10e)$$

$$z_{kb} \in \{0, 1, \dots, M\}, \forall k \in \mathcal{K}, \forall b \in \mathcal{B}, \quad (10f)$$

where $\Pr \{\cdot\}$ evaluates the probability of the input and p_0 is the tolerable outage probability of the RB-URLLC links. $P_{kb}^{\max}$ and $P_{nb}^{\max}$ are the maximum transmission power of the RB-EMBB and RB-URLLC links, respectively. Constraints (10a) represent the reliability requirements for the URLLC users. Constraints (10d) are the proportional rate constraints. $\varphi_1 : \varphi_2 : \dots : \varphi_K$ are the normalized proportionality constants where $\sum_{k=1}^K \varphi_k = 1$. (10e) is the eMBB user scheduling indicator defined in formula (5). Finally, constraint (10f)

1: Determine the number of RB N_k to be initially assigned to each user.
 Initial the number of RBs N_k per user satisfied: $N_1 : N_2 : \dots : N_K = \varphi_1 : \varphi_2 : \dots : \varphi_K$,
 and denote Gamma Vector = $[\varphi_1, \varphi_2, \dots, \varphi_K]$.
 1.1: for $k \in K$ do $N_k = \lfloor \varphi_k N \rfloor$, and all the allocated RB are defined as $\sum_{k=1}^K N_k$. As a result, there are $N^* = N - \sum_{k=1}^K N_k$ unallocated RB resources.
 end for
 1.2: for $i = 1 : K$ do
 If $N_k = 0$, do $N_k = 1$, $N^* = N^* - 1$; End if
 end for
 2: Assign the RBs to each user in a way based on the proportionality.
 2.1 for $k = 1 : K$
 assign the user with the unallocated rb that has the maximum gain, and $N_k = N_k - 1$
 end for
 2.2 for $k = 1 : k$ and $N_k \neq 0$, compute the capacity divided by the Gamma Vector, and according to the greedy policy, in each iteration gets the least one and to choose the best rb for it.
 end for
 3. Assign the remaining RBS according to the effective channel SNR from good to poor of all the users, and each user can get at most one unassigned RBs, which can balanced achieving proportional fairness while increasing overall capacity.

ALGORITHM 1: The algorithm of RB allocation for eMBB users

ensures that the number of punctured minislots from RB b can take any integer number less than M .

3. Proposed Solution

The optimization problem in (10) is an NP-hard combinatorial optimization problem with nonlinear constraints. To address the problem, we exploit certain simplifications to make the problem tractable.

We decouple the solution into two resource allocation steps. First, we allocate RB resources for eMBB users, we assume all the EMBB users have the same transmit power which meet the constraints (10b), and the RB allocation was determined by allowing each eMBB user to choose RB resource according to channel condition and its proportionality. The eMBB user with the least proportional capacity gets the priority to choose RBs in each turn. After the RB allocation, the problem in (10) is then simplified into a maximization over variables z_k and P_{nb} given by

$$\max_{\{z_{kb}\}} E \left(\sum_{k=1}^K \sum_{n \in \Omega_k} B \left(1 - \frac{z_k}{M} \right) \log_2(1 + P_{kb} H_{kb}) \right), \quad (11)$$

$$\text{s.t. Pr } \{r_{nb} \leq r_0\} \leq p_0, \forall n \in \mathcal{N}, \forall b \in \mathcal{B}, \quad (11a)$$

$$0 \leq P_{nb} \leq P_{nb}^{\max}, \quad (11b)$$

$$z_k \in \{0, 1, \dots, M\}, \forall k \in \Omega_k, \quad (11c)$$

where Ω_k refers to the set of RBs assigned to eMBB user k , r_{nb} is as defined in (5). Then, we shall combine Equations (5) and (11) to solve the optimization problem as described in part 3.2.

4. Proposed Solution

In this section, we propose an RB allocation scheme that takes into account the needs of eMBB and URLLC users. The program consists of two phases, as follows:

Phase 1. Set up RB allocation for eMBB users

Phase 2. Assign the minislot for URLLC users and calculate the transmission power of URLLC users that ensures the reliability constraint

4.1. RB Allocation for eMBB Users. In this phase, we first assign the RBs to each user in a way based on the proportionality and then propose an RB allocation algorithm based on the greedy algorithm proposed in paper [1, 10]. The algorithm in this paper is improved to solve the problem so that the allocation of resources cannot be completed normally when the number of resources is relatively low.

The complete algorithm process is listed in Algorithm 1.

4.2. URLLC Minislot Allocation. In this section, we focus on the second phase of the RB allocation scheme. The primary task at this stage is to assign the minislot for URLLC users and calculate the transmission power of the URLLC user that ensures the reliability constraint.

4.2.1. URLLC Users' Power Allocation. In Section 2.2, we analyses the reliability of URLLC users and defined the outage probability in (9). Given a puncturing pattern and substituting the channel model (4) in (9), we can expand the formula as:

$$P \left(B \frac{\sum_{i=1}^M z_{ni}}{M} \log_2(1 + P_{nb} H_{nb}) \leq r_0 \right) \leq p_0. \quad (12)$$

And the equivalence formula is:

$$P\left(\frac{P_{nb}}{\sigma^2 T} g_{nb} \leq e^{r_0 / \left(B \left(\sum_{i=1}^M z_{ni} / M\right)\right)} - 1\right) \leq p_0. \quad (13)$$

The frequency selective multipath channel is modelled between the links of URLCC n th users and both RBs, and g_{nb} is the channel power gain with an exponentially decaying profile.

Setting $\exp(r_0 / (B \sum_{i=1}^M z_{ni} / M)) = R$ and the part of probability in (12) becomes

$$P\left(g_{nb} \leq \frac{\sigma^2 T}{P_{nb}} (R-1)\right) = \int_0^{(\sigma^2 T / P_{nb})(R-1)} e^{-g_{nb}} dg_{nb} \quad (14)$$

$$= 1 - e^{-(\sigma^2 T / P_{nb})(R-1)},$$

substitute (13) into the inequality of (13), and we obtain

$$1 - p_0 \leq e^{-(\sigma^2 T / P_{nb})(R-1)}. \quad (15)$$

Then, the power allocation problem of the URLLC users can be derived from (14) as

$$P_{nb} \geq \sigma^2 T \frac{e^{r_0 / ((B/M) \sum_{i=1}^M z_{ni})} - 1}{\ln(1/(1-p_0))}. \quad (16)$$

Therefore, the minimum transmission power under the limitation of user outage probability of URLLC users is:

$$P_{nb}^{\min} = \sigma^2 T \frac{e^{r_0 / ((B/M) \sum_{i=1}^M z_{ni})} - 1}{\ln(1/(1-p_0))}. \quad (17)$$

4.2.2. Resource Assignment for URLLC Users. In this paper, for each eMBB user occupying one or more RB, a better channel condition minislot can be assigned to a URLLC user, and a URLLC user occupying one RB resource can be in multiple minislots. The distribution process is as follows:

Step 1. The URLLC users are generated according to a Poisson process.

Step 2. From all the RB resources that are selected by the i th EMBB users, find the one with the best channel parameters, denoted as $H_{i-\text{MAX}}$, $i = 1, 2, \dots, K$.

Step 3. Sort $H_{i-\text{MAX}}$ in a descending order and allocate the minislot of the first n users to all the URLLC users. If $n > K$, $n = n - K$, repeat Step 2 and Step 3.

Step 4. According to Equation (17), assign the transmitted power $P_{nb}^{\min}$ for the URLLC user.

FIGURE 1: A generation diagram of eMBB and URLLC users.

5. Simulation Results

5.1. Simulation Parameters. We consider a wireless network, where one gNB is deployed at the centre of the coverage area. A number of eMBB users are distributed randomly within the coverage area. There are K RBs in the gNB, and each RB is composed of 12 subcarriers, and each subcarrier has an SCS of 15 kHz. Thus, the bandwidth of each RB is 180 kHz. We consider the number of URLLC users in each slot, which satisfies the Poisson distribution with parameter λ . Figure 1 shows a generation diagram of eMBB and URLLC users. In the figure, $K = 10$ and $\lambda = 2$.

The frequency selective multipath channel is modelled as consisting of six independent Rayleigh multipaths with an exponentially decaying profile as paper [10]. A maximum delay spread of $5 \mu\text{s}$ and maximum doppler of 30 Hz are assumed. The total bandwidth as 5 MHz. M-QAM modulation is used and $\text{SER} = 10^{-3}$, giving an SNR gap $\Gamma = (1/3) [Q^{-1}(0.001/4)]^2 = 4.03$. A total of 1000 different channel realizations are used in a time slot. For each channel realization, a set of proportionality constants $\gamma_k = \varphi_k / \min \varphi_k$ are assigned to each eMBB user. In this simulation, the constants are expressed as integers and satisfies the following conditions as [10]:

$$\begin{aligned} P\left(\frac{\varphi_k}{\min \varphi_k} = 1\right) &= 0.5, \\ P\left(\frac{\varphi_k}{\min \varphi_k} = 2\right) &= 0.3, \\ P\left(\frac{\varphi_k}{\min \varphi_k} = 4\right) &= 0.2. \end{aligned} \quad (18)$$

5.2. Ergodic Capacity. Figure 2 shows the ergodic capacity of the gBS for all the eMBB users under different conditions,

FIGURE 2: The ergodic capacity of the gBS for all the eMBB users under different conditions.

FIGURE 3: The outage probability of URLLC users.

where the ergodic capacity expression is given by (7). We first study the curve “without gamma,” which represents the equal opportunity of all K users when allocating RB resources, and “with gamma” represents the gamma conditions. It can be seen from the figure that the capacity performance of the system without gamma conditions is better than the performance under the condition of gamma constraint. Similarly, when there are URLLC users, the ergodic

capacity of the gBS for all the eMBB users declines as a part of the minislot allocated to URLLC users. In the simulation, the tolerable outage probability of the RB-URLLC links is $p_0 = 0.0001$.

Figure 3 shows the outage probability of URLLC users. It can be seen from the figure that under certain user QoS conditions, when the transmission power is low, it cannot meet the user’s QoS requirements, but the resource assignment for

URLLC users can ensure the performance of the system's middle-end probability, and achieve the user's QoS requirements.

6. Conclusions

In this paper, we studied the coexistence problem of eMBB and URLLC users in 5G networks. We presented the time-frequency structure of the transmission frame based on 5G standards and formulated the joint eMBB/URLLC resource allocation problem. In particular, we proposed a joint resource allocation algorithm that can satisfy both the eMBB user rate and URLLC interrupt probability requirements. Through the simulation, we realized and verified the algorithm.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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