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Dynamic resource allocation schemes for eMBB and URLLC services in 5G wireless networks

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Abstract: The fifth generation (5G) of wireless networks features three core use cases, namely ultra-reliable and low latency communications (URLLC), massive machine type communications (mMTC), and enhanced mobile broadband (eMBB). These use cases co-exist in many practical scenarios and compete for the same set of time and frequency resources, resulting in a natural trade-off in their performance. In this paper, a network supporting both URLLC and eMBB modes of operation is studied. To guarantee the ultra low latency requirement of URLLC, a dynamic resource allocation scheme indicated by a two-dimensional bitmap is proposed. This approach is capable to achieve finer granularity as well as lower false cancellation rate compared to the state-of-the-art methods. A novel power control and indication method is also proposed to dynamically provide different power control parameters to the user equipment (UE), while guaranteeing the reliability requirement of URLLC and minimizing the impact to eMBB. In addition, we devise a dynamic selection mechanism (DSM) to accommodate diverse scenarios, which is empowered with load prediction to become more intelligent. Our extensive system-level simulation results for eMBB-URLLC co-existence scenarios showcase that the perceived throughput of eMBB UEs is increased by 45.3%, while about 13.3% more UEs are enjoying URLLC services with at most 84% transmit power savings compared to the state-of-the-art methods.

Key words: the fifth generation (5G); co-existence; enhanced mobile broadband (eMBB); multiplexing; resource allocation; power control; ultra-reliable and low latency communications (URLLC); uplink

1 Introduction

Wireless communication networks are serving end users and vertical industries in a growing number of scenarios, contributing to a more digitized and smarter society. The requirements for ultra-reliable and low latency communications (URLLC) and enhanced mobile broadband (eMBB) have driven the two major scenarios supported by the fifth generation (5G) of wireless systems[1, 2]. Emerging mobile broadband services which demand large bandwidth, such as ultra-high definition streaming and 3D virtual reality (VR), are mainly supported by eMBB, providing ultimate communication experience for end-user customers. On the other hand, URLLC is designed to empower services which require low latency transmissions and extremely reliable connections, such as autonomous driving for unmanned vehicles, industrial automation for smart factories, and remote surgeries for hospitals. In fact, this use case can support communications with one-way latency up to 1 ms and an outage probability of 10^{-5}.

In reality, different types of services co-exist and compete for same sets of resources. As reflected by the current 5G network deployment, the priority of

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URLLC services is deemed to be always higher than that of eMBB services[3−5], due to the fact that the former need to provide stringent guarantees on latency and reliability. When URLLC and eMBB co-exist in the same network, the URLLC scheduling and resource allocation offered by 5G base stations, i.e., the next-generation NodeB (gNB), will inevitably conflict with eMBB. In order to meet the demanding URLLC’s latency requirements, the gNB usually allocates appropriate resources to it as soon as possible after a relevant service request appears. However, there may not be enough uplink resources to allocate to the URLLC user equipments (UEs), in cases where all of them are allocated in advance for eMBB transmissions. Under such scenarios, the URLLC requirements for low latency and high reliability might not be guaranteed[6, 7]. Thus, it is of great practical value to design resource allocation schemes handling efficiently the eMBB and URLLC co-existence. It is noted that the resource allocation problem exists for both downlink (DL) and uplink (UL) communication directions, however, in this paper, the UL direction is the focus for our study.

To solve the URLLC and eMBB co-existence problem, power control (PC) and UL cancellation indication (ULCI) mechanisms have been introduced by the third generation partnership project (3GPP) protocols, as two independent solutions to multiplex the UL resources between the URLLC and eMBB transmissions[8]. Although these two baseline methods can alleviate the conflict between these two key services, they have some obvious inherent disadvantages. Specifically, ULCI is implemented based on a semi-static two-dimensional (2-D) bitmap. However, URLLC services usually appear in a dynamic and random way, rendering the semi-static pattern very problematic to model the problem and meet the corresponding requirements[9]. For the PC method, the power control parameters are again configured in a semi-static mode via higher layer signaling, hence, power boosting is conducted using a fixed value. Even if gNB schedules URLLC transmissions in a flexible manner, the resource overlapping proportion between URLLC and eMBB service is uncertain. For some practical cases where the overlapping is not significant, the fixed configuration of the power boosting value can cause a waste in transmission power and degrade the performance of eMBB services[10]. Since there is a constraint on the total transmission power of the gNB, it cannot further boost power to protect URLLC when the channel quality is poor[11]. This renders PC-based methods not applicable to all cases. In Ref. [12], both PC and ULCI were proposed to be enabled. In this way, the performance of eMBB and URLLC transmissions can be improved to certain extent, but the URLLC UE transmission power will be increased as if enabling PC alone. This method is still not applicable to the situation that there exist multiple resource overlapping proportions between URLLC and eMBB, especially when the URLLC and eMBB services are overloaded. Currently, all the existing literature studying the issue of resource allocation between eMBB and URLLC falls short in terms of power consumption and performance degradation. This study focuses on analyzing the causes of the above technical issues and providing optimized solutions to mitigate them.

In this paper, a dynamic pattern cancellation indication (DPCI) method is proposed for the UL direction to address the shortcomings of ULCI and enhance it accordingly. The major difference between the proposed DPCI method and the state-of-the-art ULCI is the replacement of the current semi-static bitmap pattern with a dynamic one, so that the indication pattern can be adjusted according to the service arrival, hence, leading to more accurate cancellation indications in a more flexible manner. Under the same assumption that URLLC always has higher priority than eMBB, the proposed dynamic indication can reduce the false indication rate and better protect the eMBB transmissions. A resource-occupancy based power control (ROPC) is also proposed to enhance the traditional PC method. With this method, the gNB is able to dynamically indicate different PC parameters to UEs on different sets of time-frequency resources, which will further guarantee the low latency and high reliability of URLLC, while protecting eMBB services. Furthermore, a dynamic selection mechanism (DSM) between the two proposed methods, namely the DPCI and ROPC, is proposed. This approach can select the best solution for a given environment and demand for resources by the two types of services, to achieve better overall system performance under complicated scenarios. Different from simply enabling both DPCI and ROPC, the proposed DSM selects the best method according to the channel quality conditions in real time, yielding significant transmission power savings for URLLC-operating UEs.

The rest of the paper is organized as follows. Section 2 introduces the system model as well as the problem formulation. Section 3 describes in detail the proposed DPCI and ROPC schemes as well as their DSM. Extensive system-level simulation results are presented in Section 4, including their detailed analysis. Finally, Section 5 concludes the paper.

2 System model and evaluation methodology

The 5G new radio (NR) interface includes two-way communications, in the uplink and downlink directions. For downlink transmissions, the time-frequency resources are usually sufficient for both URLLC and eMBB services, hence, this direction is normally not the bottleneck of the network deployment. Thus, the co-existence of these two types of services in the downlink does not need special studies, since the competition for resources is not severe. However, the uplink system performance when URLLC and eMBB services co-exist is critical and is the subject study of this paper.

We consider a cellular communication system comprising N gNBs which are evenly distributed in an area of interest, each having K_r receiving antenna. It is assumed that each gNB corresponds to a cell. In every cell, there exist M UEs, each equipped with K_t transmitting antennas. The gNB schedules URLLC and eMBB services to the UEs belonging to its cell: it schedules only eMBB transmissions to eMBB UEs and only URLLC transmissions to URLLC UEs. In other words, the two types of UEs represent the two types of devices which only require a distinct type of service. The number of UEs in each cell is M, where the number of URLLC UEs is denoted by M_{URLLC} while the number of eMBB UEs by M_{eMBB}. No other types of UEs are considered, thus holds $M_{URLLC} + M_{eMBB} = M$. Unlike eMBB, which demands a steady and large bandwidth for a relatively long period of time, the URLLC service usually appears in a sporadic manner. The packet size of URLLC services is assumed to be B bytes, and the average arrival rate is 1 packet per T ms. The data packet type of eMBB services is considered as file transfer protocol model 3 (FTP3) with Poisson distribution, and the size of each packet is configured according to the Pareto distribution[13]. The size of the eMBB packet is assumed to reside between B_{min} and B_{max}. In the considered network deployment, UEs with two service types are randomly distributed in each cell, and the UEs can be either indoors or outdoors. Among them, indoor UEs account for the $i\%$ of the total number of UEs and outdoor UEs account for the $o\%$ of it.

In the time domain, flexible sub-frame structure is considered for the scheduling of URLLC and eMBB UEs. Normally, a URLLC service has a stringent requirement for latency, so that the time granularity for the scheduling of URLLC service is one mini-slot. In order to simplify the system model, the eMBB service is scheduled by one slot. This implies that the transmission time interval (TTI) for URLLC and eMBB UEs is different. Figure 1 shows an example of the time domain structure of both services, where the scheduling time granularity of eMBB is set to a complete slot with 14 orthogonal frequency-division multiplexing (OFDM) symbols, while the scheduling time granularity of URLLC is set to a mini-slot with 2 OFDM symbols. The monitoring interval of the UL cancellation signaling is equal to that of the physical downlink control channel (PDCCH)[14]. For the frequency domain resource allocation, both continuous and non-continuous resource allocation are considered, and the smallest scheduling unit in frequency domain is a resource block (RB).

In order to simplify the evaluation process, this paper provides some basic assumptions for the two solutions based on ULCI and PC. For the ULCI-based scheme, if

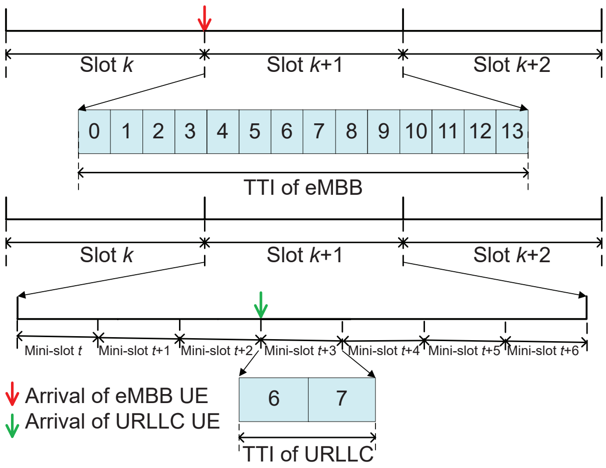

Fig. 1 TTI configuration for scheduling UEs requesting URLLC and eMBB services.

part of UL eMBB transmission is dropped due to collision, the remaining eMBB transmission is discontinuous and almost impossible to be decoded. Therefore, the whole eMBB transmission is assumed as dropped. For the PC-based scheme, it is supposed that once the URLLC transmission overlaps with the eMBB transmission, the URLLC UE increases the transmit power by P dB. In the considered model, each PDCCH monitoring occasion contains 32 control channel elements. The search space set of the UL cancellation signaling is configured at the aggregation level (AL) = $\{1,2,4,8,16\}$, and the corresponding candidate numbers are $\{8,4,2,1,1\}$, respectively. The UL cancellation signaling is carried by a public PDCCH, and the transmission power control signaling messages are carried by a dedicated PDCCH.

In the system performance evaluation model, the minimum mean-square error interference rejection combining (MMSE-IRC) algorithm is used as the gNB reception scheme[15]. Let $\boldsymbol{s}_1$, $\boldsymbol{y}$, and $\boldsymbol{W}$ represent the complex-valued K_t-element transmit signal vector, the complex-valued K_r-element signal received at the gNB antenna elements, and the complex-valued $K_r \times K_t$ combining matrix, respectively. The mean square error between the combined received signal and the transmitted one is the objective function of the MMSE-IRC receiver, which is defined as

$$\min_{\boldsymbol{W}} E\left[\left(\boldsymbol{W}^{\mathrm{H}}\boldsymbol{y}-\boldsymbol{s}_1\right)^{\mathrm{H}}\left(\boldsymbol{W}^{\mathrm{H}}\boldsymbol{y}-\boldsymbol{s}_1\right)\right] \tag{1}$$

When seeking for the optimal solution according to the gradient, we make full use of the information of the known interference channel matrix (via a dedicated channel estimation process), and the MMSE-IRC weighted matrix can be obtained according to expression

$$\boldsymbol{W}^{\mathrm{H}} = \boldsymbol{H}_1^{\mathrm{H}}\left(\boldsymbol{H}_1\boldsymbol{H}_1^{\mathrm{H}} + \frac{I_{oc}}{E_s}\boldsymbol{H}_2\boldsymbol{H}_2^{\mathrm{H}} + \frac{N_0}{E_s}\boldsymbol{I}_{K_t}\right)^{-1} \tag{2}$$

where $\boldsymbol{H}_1 \in \mathbb{C}^{K_r \times K_t}$ denotes the channel matrix between the serving cell and the gNB receiver and $\boldsymbol{H}_2 \in \mathbb{C}^{K_r \times K_t}$ is the channel matrix between a UE in the interfering cell and the same receiver. E_s represents the average power of the transmitting symbols, whereas the interference and noise powers are denoted by N_0 and I_{oc}, respectively. Finally, $\boldsymbol{I}_{K_t}$ is the $K_t \times K_t$ (with $K_t \geqslant 2$) identity matrix. When N_{int} interference cells are present in the system model, the MMSE-IRC weighted matrix formula can be extended as follows:

$$\boldsymbol{W}^{\mathrm{H}} = \boldsymbol{H}_1^{\mathrm{H}}\left(\boldsymbol{H}_1\boldsymbol{H}_1^{\mathrm{H}} + \sum_{n=2}^{N_{int}}\frac{I_{oc}}{E_s}\boldsymbol{H}_n\boldsymbol{H}_n^{\mathrm{H}} + \frac{N_0}{E_s}\boldsymbol{I}_{K_t}\right)^{-1} \tag{3}$$

3 Proposed resource allocation schemes

In Fig. 2, a typical example of the ULCI mechanism for multiplexing URLLC and eMMB transmissions in the UL is shown. The eMBB transmission is scheduled by the UL grant #1, while the URLLC one by the UL grant #2, and the resources for both services are partially overlapping. In the meanwhile, preempted information is transmitted to all eMBB UEs by the ULCI. If the ULCI is successfully decoded by the

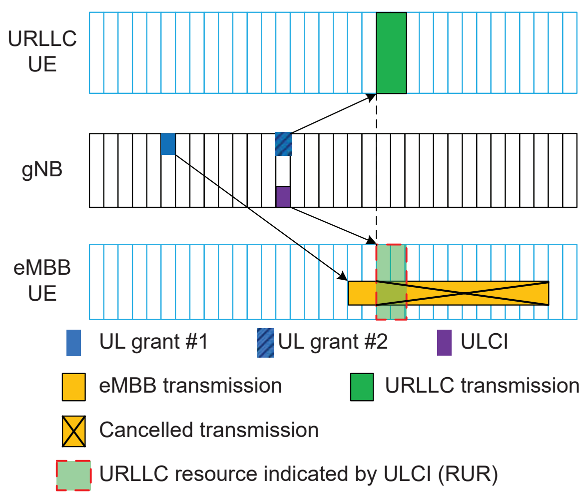

Fig. 2 Workflow of the ULCI mechanism.

eMBB UE, its UL transmission will be canceled, and only the eMBB transmission before the arrival of the URLLC service is reserved. In this paper, the resource region indicated by the ULCI is defined as reference UL resource (RUR).

Another UL multiplexing transmission solution is based on PC. According to this scheme, when the URLLC service conflicts with the eMBB service, the gNB notifies the URLLC UE to increase its transmission power. For this scheme, the eMBB transmission is not canceled, and it is possible for the gNB to correctly decode the eMBB transmission block without re-transmission. However, the URLLC transmission will cause serious interference to the eMBB one. Compared with the ULCI mechanism, it becomes apparent that the PC-based co-existence scheme is more favorable to eMBB transmissions. On the contrary, the ULCI focuses on ensuring the performance of URLLC transmissions.

3.1 Dynamic pattern cancellation indication

In most cases, the distribution of URLLC UEs in a cell is irregular. Both URLLC and eMBB UEs are randomly distributed at both the edge and center of the serving cell. The channel quality of the cell-center UEs is ideal, so the gNB tends to allocate more frequency domain resources to them in a short time for latency reduction. This makes it reasonable for the gNB to allocate a time-frequency resource which spans few OFDM symbols, while containing multiple sub-carriers, for the cell-center UEs. On the other hand, UEs at the edge of a cell may suffer from more severe inter-cell interference and path loss. To meet reliability requirements, the gNB allocates less frequency resources, but more time domain symbols to those UEs. Then, a time-frequency resource, which spans over multiple OFDM symbols, but contains few sub-carriers, is more suitable for cell-edge UEs. A gNB resource allocation example to UEs lying at the cell center and edge is illustrated in Fig. 3. The RUR is divided into 7 parts in the time domain and 4 parts in the frequency domain according to a 2-D bitmap with size 28 bits, including 28 sub-blocks. The first green resource from the right is allocated by gNB to the cell-center UE, and occupies 2 time-domain and 3 frequency-domain sub-blocks. The second green resource block is allocated to the cell-edge UE, occupying 2 time-domain and 2 frequency domain sub-blocks. In addition, according to the actual network emphasis on URLLC service features, URLLC services cover a variety of different application scenarios, such as factory automation, as well as power distribution and transmission industries. In different application scenarios, the gNB allocates resources in accordance with the service requirements. For example, a URLLC transmission with large packet size and high reliability requirements needs more time-frequency resources than the transmissions with small packet sizes or low reliability requirements. This implies that various URLLC services may co-exist in one cell in practice.

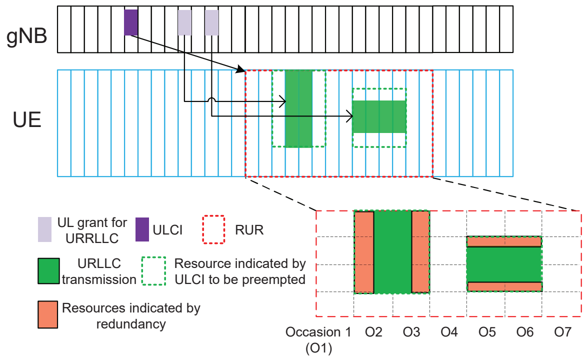

Fig. 3 A gNB allocating resources to URLLC UEs lying at the cell center and edge.

There are multiple ULCI resource indication modes, such as 7×4 or 2×7 time-frequency resource sub-blocks. According to the actual RUR size and the specific features of the URLLC service, one ULCI resource indication mode can be configured semi-statically by the gNB according to a 2-D bitmap. However, the semi-static 2-D bitmap cannot provide flexible frequency-domain granularity. Once the URLLC service does not match the resource sub-block, a large number of eMBB transmission resources will be cancelled unnecessarily. In order to reduce the eMBB time-frequency resources that are cancelled due to false indication, the resource indication mode needs to be dynamically configured according to a dynamic 2-D bitmap. The core idea of the proposed dynamic approach capitalizes on the fact that the time-domain occasions actually occupied by the URLLC transmission are valid for further indication in the frequency domain. Therefore, the proposed scheme needs first to indicate the time domain occupied by the target transmission, and the time-frequency resources corresponding to the time domain will be indicated by the dynamic 2-D bitmap. More specifically, the bit structure of the proposed DPCI approach is the following.

- Q bits are used for indicating the time-domain occasions occupied by the URLLC transmission. This number equals to the number of time-domain occasions per RUR.
- $\boldsymbol{C}$ is an $a \times b$ bitmap for frequency-domain indication, i.e., the occupied time-domain occasions are divided into $a \times b$ portions. Each portion is indicated by a bit in the 2-D bitmap, wherein a represents the number of occupied time-domain occasions and b is the number of frequency-domain resources. Both of these values are determined according to the indication of Q bits dynamically.

As shown in Fig. 4 for an example DPCI, where $Q = 7$, $a = 2$, and $b = 10$, the total number of indication bits is 27. Compared with ULCI, which requires 28 indication bits, the frequency-domain indication granularity (FDIG) of DCPI is finer, and the two methods have similar signaling overhead. Finer granularity can better match the URLLC services, which can reduce the time-frequency resources that are cancelled falsely for eMBB services; this protects eMBB transmissions in a better way. Table 1 shows the correspondence between the occupied time domain occasions (OTDOs) and FDIG of the ULCI and DPCI mechanisms. It can be concluded that, when the

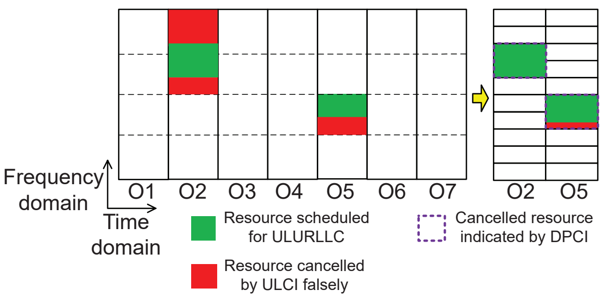

Fig. 4 Resources indicated by an example of the proposed dynamic 2-D bitmap.

Table 1 Correspondence between the indication granularity and the number of OTDOs for both ULCI and DPCI mechanisms.

ULCI		DPCI	
Number of OTDOs	FDIG	Number of OTDOs	FDIG
1	$\frac{1}{4}$	1	$\frac{1}{21}$
2	$\frac{1}{4}$	2	$\frac{1}{10}$
3	$\frac{1}{4}$	3	$\frac{1}{7}$
4	$\frac{1}{4}$	4	$\frac{1}{5}$
5	$\frac{1}{4}$	5	$\frac{1}{4}$
7	$\frac{1}{4}$	7	$\frac{1}{3}$

number of OTDOs is less than 5, the minimum frequency-domain indication granularity of each time-domain resource of DPCI is finer than that of the ULCI. For example, when the OTDOs number is 3, the number of indication bits for each occasion is $(28-7)/3 = 7$, and the minimum indication granularity is $1/7$, which is smaller than $1/4$.

3.2 Resource-occupancy based power control

As previously mentioned, to ensure the flexibility of URLLC transmissions, the gNB needs to schedule the most appropriate time-frequency resources to the URLLC UE. However, those resources might have been already allocated to an eMBB service. In the PC-based mechanism, once the resource dedicated to the URLLC transmission overlaps with that of eMBB, the URLLC transmission power increases by P dB. A 6 dB increase is frequently used in the practical systems.

In practical scheduling cases, the interference from eMBB transmissions to URLLC ones varies. As shown in the example in Fig. 5, the transmission power of the eMBB UEs may be configured with different power control parameters under different scenarios. The proportion of the overlapped resources for the URLLC and the eMBB services under different RURs may also vary due to time-varying scheduling resources for URLLC. Therefore, when the URLLC transmission power increases by a fixed value, it can be severely wasted or insufficient, but can also affect the normal transmission performance of eMBB services. Compared with this fixed power adjustment, the

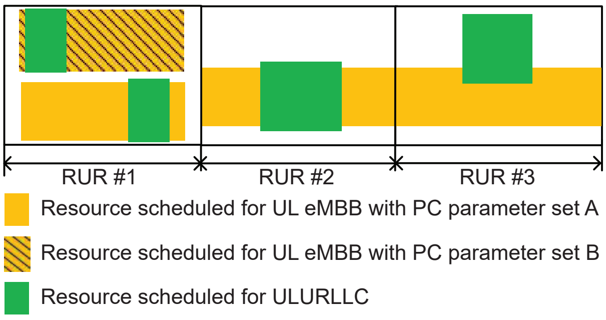

Fig. 5 Different overlapping situations between URLLC and eMBB transmissions.

proposed ROPC scheme provides increased flexibility. By defining different power control parameters for different resource groups, there are multiple options for a URLLC UE to boost its transmission power. Additionally, the power is used efficiently. The URLLC UE increases its power transmission according to the proportion of overlapped resources for the all URLLC services in ROPC, so that to avoid wasting to some extent. In the following two subsections, we detail the latter two improvements offered by ROPC.

(1) **Flexible power control:** The gNB can configure multiple groups of time-frequency resources to a UE, and this can be conveyed to it via dynamic signaling. Each time-frequency resource indicator corresponds to a time-frequency resource group that matches different power control parameter sets. The URLLC UE determines its own transmit power according to the power control parameter set corresponding to the time-frequency resource group overlapping with the eMBB transmission. As shown in Fig. 6, a time-frequency resource indication field set is used by the control information of the ROPC. The field set contains multiple time-frequency resource indication fields, with each associated with a group of time-frequency resources. The gNB configures the power control parameters for each group according to the radio resource control signaling. When the time-frequency

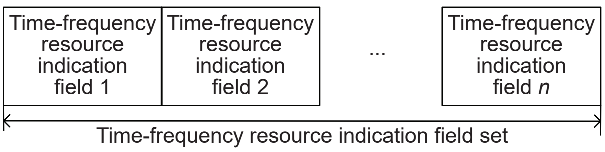

Fig. 6 Time-frequency resource indication field of the proposed ROPC scheme.

resources of the URLLC transmission overlap with one group of time-frequency resources, the respective UE increases its power according to the power control parameters corresponding to that group. In cases where the time-frequency resources of the URLLC transmission overlap with more than one group of time-frequency resources, the transmit power can be chosen as the maximum from the available value set or their average.

(2) **Power-boosting based on overlapping resources:** Multiple overlapping resource ratio thresholds are predefined in the proposed ROPC and are flexibly configured by the gNB. The proportion of overlapping resources is defined as the proportion of overlapped resources to the URLLC transmission resources. For instance, the threshold could include 10%, 40%, and 80%. According to experience, these thresholds can best distinguish the power control performance. Then, the mapping relationship between the power increment value P in dB and the actual overlapping resource proportion value x are related as follows:

$$P = \begin{cases} 0, & x \leqslant 10\%; \\ 3, & 10\% < x \leqslant 40\%; \\ 6, & 40\% < x \leqslant 80\%; \\ 9, & 80\% < x \end{cases} \tag{4}$$

For example, if the resource scheduled for URLLC contains 20 RBs and the overlapping resource equals to 10 RBs, the actual overlapping resource proportion is 50%. In this case, the transmission power of the URLLC UE will be increased by 3 dB. The power control parameters are switched by gNB dynamical configuration. The following steps describe the proposed ROPC scheme.

Step 1: When the gNB allocates time-frequency resources to a UE, it obtains the information of the URLLC time-frequency resource group that is overlapping with eMBB transmissions.

Step 2: According to the information obtained in Step 1, the gNB calculates the actual overlapping resource proportion of each URLLC time-frequency resource group.

Step 3: The gNB sends control information with the power control parameter index corresponding to each resource group, according to the computation at Step 2, to the URLLC UE.

Step 4: The URLLC UE boosts the transmitting power for each group time-frequency resource according to the index in the time-frequency resource indication field in ROPC's control information.

There are three advantages from the introduction of the overlapping resource ratio in Formula (4). The first advantage relates to the restriction of the interference caused to eMBB transmissions, which obviously improves the latter's performance. The second advantage is that the transmission power of the URLLC UE can be adjusted. Finally, different power control parameters for different transmission time-frequency resources can be used, which improves the power control accuracy. The only disadvantage is that the signaling overhead may increase, which is treated in the sequel by a dynamic selection mechanism between DPCI and ROPC schemes.

3.3 Dynamic selection of power control schemes

In most practical scenarios, URLLC and eMBB UEs co-exist in the same cell, as illustrated in Fig. 7. For the eMBB UEs, one group of them may be capable of receiving the control information of the DPCI mechanism, while others may not. Similarly, the cell-center URLLC UEs may perform ROPC without power constraints, while the cell-edge one may lack power headroom for ROPC.

According to the proposed dynamic selection mechanism, there are three options for the power control: ROPC, DPCI, and none of them. The dynamic selection can be configured to prioritize transmissions of eMBB UEs or prioritize on the power saving of URLLC UEs. If the former is selected and UEs are in good channel conditions, the gNB can choose to only schedule URLLC UEs to perform ROPC. Otherwise, it schedules eMBB and URLLC UEs to perform DPCI and ROPC, respectively. This happens because when the channel quality is good, the eMBB data are very likely to be received correctly even if the URLLC UE increases its transmission power. Therefore, if the eMBB transmission is not cancelled without performing DPCI, it would not be impacted much. On the contrary, the eMBB data may not be correctly received when the channel quality is bad. In this case, it is necessary to perform DPCI for eMBB UEs in order to ensure the performance of URLLC transmissions. If the power saving of URLLC UEs is prioritized instead, the gNB can choose to only schedule eMBB UEs to perform DPCI, if they experience good channel conditions. Otherwise, the gNB can schedule eMBB and URLLC UEs to perform DPCI and ROPC, respectively.

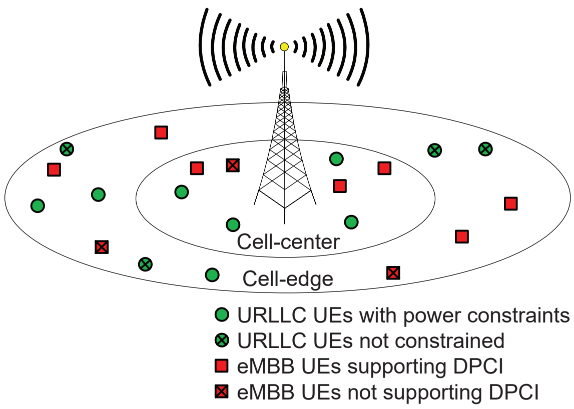

Fig. 7 A single-cell example including the distribution of the UEs in its center and cell.

3.4 Load prediction for dynamic PC-scheme selection

In practical networks, the status of a UE is constantly changing, including its location and speed within certain ranges. Channel prediction can solve the outdated channel estimation problem caused by the UE movement, leading to efficient resource allocation according to the predicted channel status, thus improving the usage of time-frequency resources. In fact, channel prediction can be used together with the proposed dynamic selection mechanism to improve the performance of both eMBB and URLLC transmissions.

The UE speed information is required in the channel prediction method adopted in this paper. As shown in Fig. 8, the potentially scheduled UE needs to periodically report its location information to the gNB. After obtaining the location of the UE before and after a period, the gNB estimates its speed v_0 as follows:

$$v_0 = \frac{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}}{t_{period}} \tag{5}$$

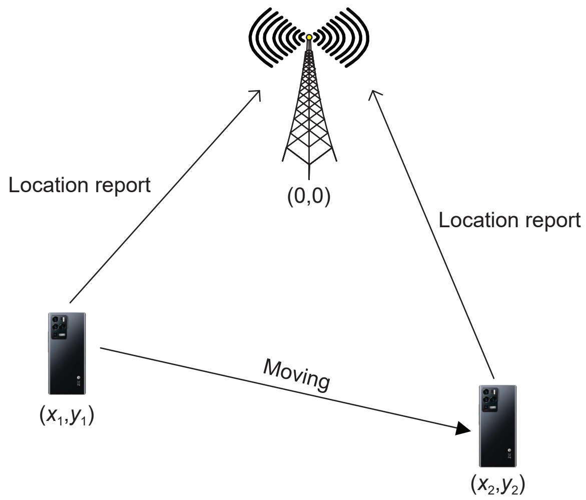

Fig. 8 Example of the positions of a mobile UE at different time intervals.

where t_{period} is the reporting period of the UE, and (x_1, y_1) and (x_2, y_2) denote its 2-D coordinates at the beginning and end of that period, respectively. A channel prediction window W is considered which is divided into n time units, and contains m subbands in the frequency domain. Particularly, the gNB measures n times the channel quality of each f-th subband in the window, and the measurements are stored in a matrix. A baseline speed v_0 is configured by the gNB according to a semi-static signaling, and v_0 is generally configured as 30 km/h based on experience. The reference channel quality of the time instant n_0 for channel prediction can be calculated as follows with $n' = \lfloor \frac{nv_0}{v_0} \rfloor$:

$$q_{n_0} = \begin{cases} \dfrac{\sum_{j=0}^{n-1} \sum_{i=0}^{m-1} q_{j,i}}{mn}, & v_0 \leqslant v'_0; \\ \dfrac{\sum_{j=0}^{n'-1} \sum_{i=0}^{m-1} q_{j,i}}{mn'}, & v_0 > v'_0 \end{cases} \tag{6}$$

where $q_{j,i}$ denotes the measured channel quality at the j-th time instant and m subband. Finally, the gNB determines which multiplexing method is chosen in accordance with the predicted channel quality, and then performs the corresponding scheduling. In addition, the resource allocation result of the UE can be modified.

4 Simulation results and discussion

To evaluate the impact of the proposed and state-of-the-art resource allocation methods, system-level simulation results are presented in this section. The conducted simulations mainly include the following aspects:

- The percentage of the number of time-domain resources occupied by a URLLC transmission per RUR.
- The minimum power increase for a URLLC UE, when its transmission can meet the reliability requirements.
- Power boosting value comparison for the different resource allocation methods as well as the proposed dynamic selection mechanism.

The system evaluation model described in Section 2 was used for the system-level simulations with the following parameters' setting. The carrier frequency was set to 4 GHz, which is a typical configuration in current 5G systems. The system bandwidth and sub-carrier spacing (SCS) were set to 40 MHz and 30 kHz, respectively, and we considered the urban macro (UMa) channel model specified in TS 38.901[16]. All parameters used in our simulations are listed in Table 2.

(1) **Number of URLLC time-domain occasions:** The percentage of the number of time-domain occasions used by URLLC transmissions (i.e., the arrival rate of URLLC services) per RUR, whose duration was set to 1 slot, is illustrated in Fig. 9 as a function of the total number of UEs in the cell. One RUR comprises 7 time-domain occasions with each occasion spanning over 2 OFDM symbols. As can be seen from Fig. 9, the percentage of 1 occasion decreases with increasing numbers of eMBB UEs, while for cases where more than one occasions are occupied by URLLC, this performance increases as the number of eMBB UEs increases. The main reason for this behavior relies on the fact that, when there are more eMBB UEs, the available time-frequency resources in the system are reduced. When a URLLC service arrives, it will overlap more time-frequency resources occupied by eMBB UEs, and hence, more time-domain occasions in the RUR will be occupied by URLLC. However, since the arrival rate of URLLC services is low, the number of occasions scheduled for

Table 2 Parameters for the system-level simulations.

Parameter	Value or configuration
Central carrier frequency	4 GHz
Bandwidth	40 MHz
Sub-carrier spacing	15, 30, 60, 120 kHz
Channel model	UMa in TR 38.901
Antenna port configuration	4 antenna ports for receiving and 2 for transmitting
gNB reception algorithm	MMSE-IRC
Cell load	Number of eMBB UEs: $K_{\text{eMBB}} = 10$, number of URLLC UEs: $K_{\text{URLLC}} = \{5,6,7,8,9,10,20\}$, $\Omega = (K_{\text{eMBB}}, K_{\text{URLLC}})$
TTI configuration	2, 3, 4 OFDM symbols for URLLC, 14 OFDM symbols for eMBB
HARQ	Max number of transmissions: 4, target BLER equals to 0.01% (URLLC) or 10% (eMBB)
Traffic model for eMBB transmission	Packet arrival per UE: FTP Model 3 Packet size: 50−600 bytes
Traffic model for URLLC transmission	Packet arrival per UE: Periodic with arrival rate of 1 packet per 2 ms Packet size: 32 bytes
UE distribution	80% outdoors, 20% indoors
Configuration of eMBB UEs	90% support DPCI, 10% do not support DPCI

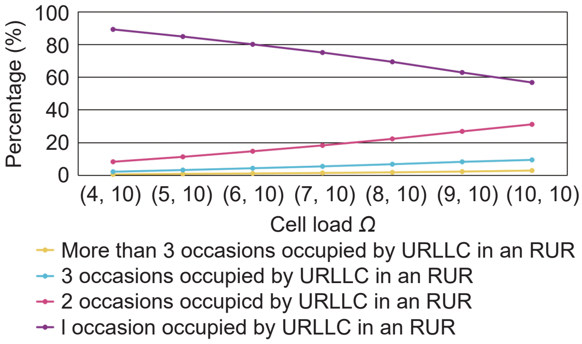

Fig. 9 Percentage of the number of time-domain resources occupied by a URLLC transmission during an RUR versus the total number of UEs, Ω, in the cell.

URLLC transmissions will be relatively small. It is also evident from Fig. 9 for 94% of the cases that URLLC services occupy less than 3 time-domain occasions in an RUR. Based on Table 1, it can be inferred that the frequency-domain granularity can be optimized by DPCI in most scheduling cases. In other words, DPCI has more accurate indication accuracy for at least 94% of the cases.

(2) **Minimum power increment for URLLC services:** To prove the reasonableness of grading multiple values for power boosting, 100 times of URLLC and eMBB conflicts were intercepted in the system-level simulations. The repetition number for each conflict with different power value was set to 10, and a minimum power value with which a URLLC UE can meet a latency and reliability requirement was selected. If the URLLC UE cannot meet the requirement with any of the available power-boosting values, the maximum power will be selected. In the system simulation, the cell load was set to $\Omega = (10, 10)$ with respect to the number of eMBB and URLLC UEs, respectively, and the values 9 and 0 dB were the maximum and minimum boosted power, respectively. The duration of RUR was the same with that in Fig. 9. The power increase value was divided into four levels (shown in Fig. 6 with dotted lines) equal to 0, 3, 6, and 9.

It is clearly shown in Fig. 10 that the most appropriate power boosting value is not always set to 6 dB, as happens with conventional PC. The main

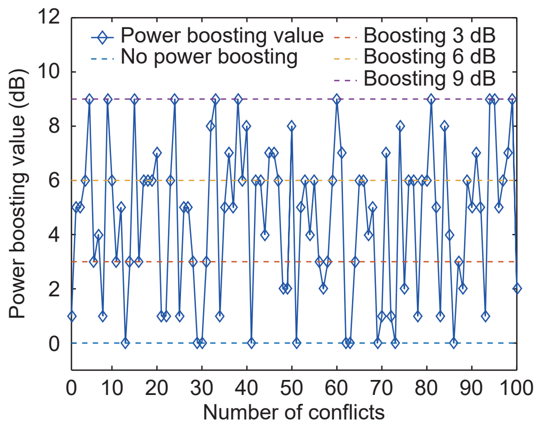

Fig. 10 Power boosting values in dB for 100 conflicts between URLLC and eMBB services.

reason is that the location of each URLLC UE is different, which causes the channel quality of each URLLC UE to be different as well. This implies that the power increase needs to ensure every different URLLC transmission. As depicted in Fig. 10, for the 17% of the conflicts, the boosting power for URLLC transmission needs to be higher than 6 dB to meet the reliability requirement, while for the 40% of the conflicts, the required power is less than 6 dB. For the proposed ROPC scheme, the 9 dB power boosting can be decided when the 6 dB increment cannot satisfy the URLLC requirements. To save power, the 0 and 3 dB power boosting values are used when channel conditions are good.

(3) **URLLC power-boosting comparisons:** The energy saving is a very important indicator for the efficient operation of wireless communication equipment[17, 18]. In our performance evaluation, we have considered URLLC UEs with typical communication equipment, and assumed that the gNB can only provide URLLC service to UE having the relevant equipment. Recall that in the conventional PC-based solution, the boosted power value for URLLC UEs is fixed at 6 dB. For the performance assessment of the proposed ROPC-based solution, we have simulated 10 000 times of collision between URLLC and eMBB services for different Ω values, and counted the average power increment by the URLLC UE. We have also simulated two scenarios with different prioritized principles for the proposed dynamic selection mechanism. In the one prioritized on performance, the average power increased by the URLLC UE is the same as that of ROPC. In the other prioritized on power saving, more than 10% of the scheduling assignments do not need perform ROPC. We have also simulated the performance of DSM with and without load prediction.

Table 3 summarizes the power boosting values for URLLC UEs. It can be seen that the power boosting of URLLC UEs increases with increasing numbers of eMBB UEs in the system, and this happens for every considered method. Clearly, when the number of eMBB UEs increases, the probability of collision between URLLC and eMBB services increases. In such cases, the URLLC UEs need to increase their power to ensure successful transmissions. This increase in the UL transmission power differs according to the resource allocation method considered. Compared with PC, the DPCI and the DSM schemes prioritizing on performance can help to save the transmission power by 0.54−1.86 dB. On the other hand, when DSM is prioritized on power saving, it can save 2.16−2.29 dB of the transmission power compared to PC. Among all schemes, the DSM assisted by load prediction exhibits the best power saving performance. It can be also seen in Table 3 that, compared with PC, the DSM with load prediction is able to save 1.23−2.03 dB and 2.23−2.60 dB of the transmission power of URLLC UEs, when it prioritizes performance and power saving, respectively. Compared with PC, the DSM with load prediction can reduce the power of at most 2.6 dB, i.e., offer 84% of power saving.

(4) **Throughput performance comparison of resource allocation schemes:** The percentage of the URLLC UEs meeting their reliability and latency requirements as well as the eMBB UE perceived

Table 3 Power boosting value and gain in dB for different resource allocation methods.

Resource allocation method	Power boosting value (dB)							Gain (dB)
	$\Omega=(5,10)$	$\Omega=(6,10)$	$\Omega=(7,10)$	$\Omega=(8,10)$	$\Omega=(9,10)$	$\Omega=(10,10)$	$\Omega=(20,10)$	
PC	6.00	6.00	6.00	6.00	6.00	6.00	6.00	−
ROPC	4.14	4.23	4.33	4.45	4.58	4.73	5.46	0.54−1.86
DSM (prioritized on performance)	4.14	4.23	4.33	4.45	4.58	4.73	5.46	0.54−1.86
DSM with load prediction (prioritized on performance)	3.97	4.07	4.19	4.31	4.38	4.43	4.87	1.23−2.03
DSM (prioritized on power saving)	3.71	3.73	3.74	3.76	3.78	3.79	4.41	1.59−2.29
DSM with load prediction (prioritized on power saving)	3.40	3.42	3.43	3.44	3.45	3.47	3.77	2.23−2.60

throughput (UPT) have been evaluated for all considered resource allocation methods. The scheduling granularity in time domain was set to 14 OFDM symbols for eMBB transmissions and 2 OFDM symbols for URLLC transmissions. For the ULCI method, the 2-D bitmap pattern was set as 7×4, which means that the RUR was divided into 7 parts in the time domain and 4 parts in the frequency domain. For PC, the power boosting value was configured as 6 dB for URLLC UEs according to the conventional PC method. In DPCI method, 7 bits were used to indicate the time-domain occasions occupied by eMBB UEs, and a 2-D bitmap pattern was dynamically set based on the number of the occupied occasions; we specifically used the patterns: 1×21, 2×10, 3×7, 4×5, 5×4, 6×3, and 7×3. For the ROPC method, the power boosting value was set to any of the 4 available levels: 0, 3, 6, and 9 dB. The common simulation parameters were set as described in Table 2. The simulation results are illustrated in Figs. 11 and 12 as well as Table 4 as function of the total number of UEs, Ω, in the cell. We have also collected results when one of the above schemes is applied.

It can be observed from Figs. 11 and 12 and Table 4

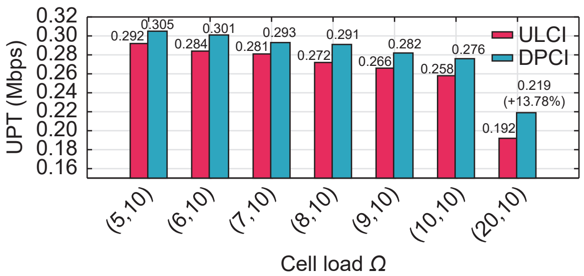

Fig. 11 Perceived throughput at the eMBB UE for ULCI and DPCI methods versus the total number of UEs, Ω, in the cell.

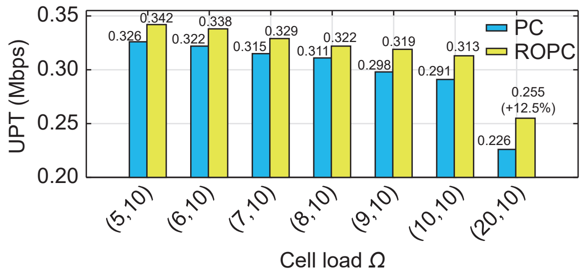

Fig. 12 Perceived throughput at the eMBB UE for PC and ROPC methods versus the total number of UEs, Ω, in the cell.

that, when the load of the cell increases, the UPT of eMBB transmissions and the percentage of URLLC UEs meeting the respective requirements decrease. When the amount of system resources are moderate, the time-frequency resources allocated to each eMBB UE reduce as the number of eMBB UEs increases. In addition, once a URLLC service collides with an eMBB one, the percentage of the interfering eMBB transmissions becomes relatively large for each eMBB UE. Therefore, the UPT of eMBB UEs gradually decreases with increasing numbers of eMBB UEs. For URLLC transmissions, as the number of eMBB UE increases, the probability of collision between URLLC and eMBB increases, and thus, the percentage of URLLC UEs meeting their respective requirements decreases.

Figures 11 and 12 also demonstrate that the performance of eMBB transmissions with PC-based methods is better than that of methods relying on cancellation indication. In all investigated scenarios, ROPC yields the best UPT performance due to its dynamic power boosting capability. In addition, it is shown that DPCI has a maximum gain of 13.78% compared with ULCI, and ROPC has a maximum gain

Table 4 Percentage of URLLC UEs satisfying reliability and latency requirements under different resource allocation methods.

Multiplexing method	Percentage (%)						
	$\Omega=(5,10)$	$\Omega=(6,10)$	$\Omega=(7,10)$	$\Omega=(8,10)$	$\Omega=(9,10)$	$\Omega=(10,10)$	$\Omega=(20,10)$
No scheme	84.37	83.11	82.14	81.07	79.78	78.64	66.71
ULCI	93.33	92.78	92.09	91.32	90.54	89.87	80.64
DPCI	93.27	92.61	91.88	91.17	90.37	89.64	80.62
PC	87.78	87.01	86.23	85.56	84.79	83.97	73.84
ROPC	88.34	87.92	87.50	87.14	86.86	86.47	76.77

of 12.50% compared with PC. Compared with ULCI, the DPCI yields better performance since it reduces the probability of erroneous cancellations of eMBB transmissions. In general, the methods based on cancellation indication affect eMBB transmissions, but they can effectively avoid interference from eMBB transmissions to URLLC ones. As can be seen from Table 4, DPCI and ULCI outperform conventional PC in terms of the performance of URLLC transmissions. In fact, the performance of both methods is similar. This happens because DPCI can cancel eMBB transmissions conflicting with URLLC as effectively as ULCI. Table 4 also showcases that the URLLC UE satisfaction percentage of ROPC is increased by 2.93% compared with PC. This is due to the fact that ROPC can dynamically boost the transmission power by 9 dB under the condition a 6 dB increment cannot guarantee normal URLLC transmissions.

(5) **Throughput performance comparison of the proposed dynamic selection mechanism and baseline methods:** Figure 13 and Table 5 include the UPT results of eMBB transmissions and the percentage of UEs satisfying the reliability and latency requirements for URLLC transmissions, respectively, for the baseline resource allocation schemes and different versions of the proposed DSM one. As shown, a similar trend with the results presented in the previous Section 4 is exhibited. It is also evident that the proposed DSM empowered by load prediction outperforms, in terms of UPT of eMBB transmissions, the baseline methods and the basic versions of DSM for all considered Ω values. For the eMBB transmission performance, it can be observed that the DSM version prioritizing on power saving with load prediction has a maximum gain of 45.3% and 23.5% compared with ULCI and PC, respectively. The source

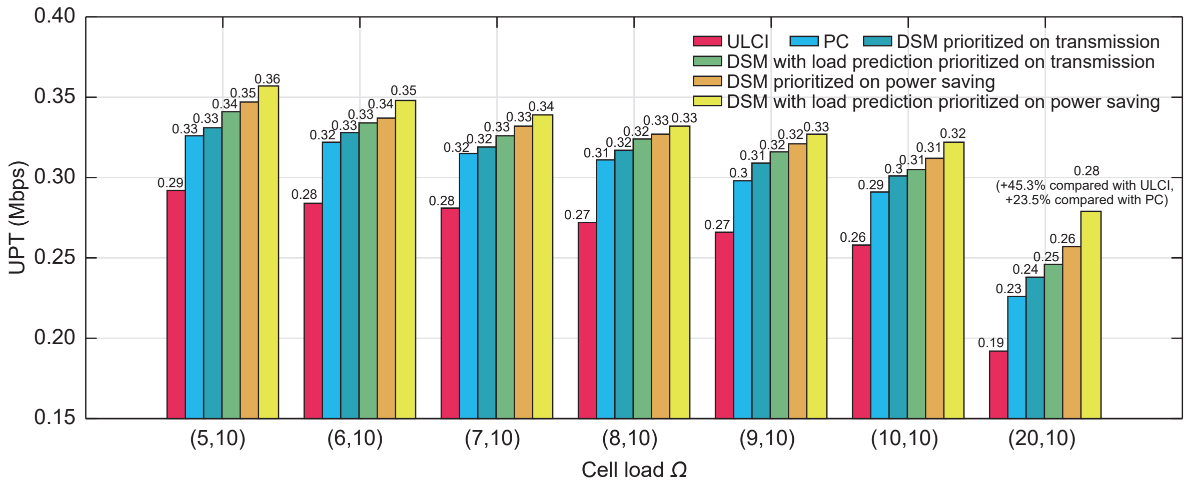

Fig. 13 Perceived throughput at the eMBB UE for all considered resource allocation methods versus the total number of UEs, Ω, in the cell.

Table 5 Percentage of UEs satisfying reliability and latency requirements for URLLC transmissions under different resource allocation methods.

Resource allocation method	Percentage (%)						
	$\Omega=(5,10)$	$\Omega=(6,10)$	$\Omega=(7,10)$	$\Omega=(8,10)$	$\Omega=(9,10)$	$\Omega=(10,10)$	$\Omega=(20,10)$
ULCI	93.33	92.78	92.09	91.32	90.54	89.87	80.64
PC	87.78	87.01	86.23	85.56	84.79	83.97	73.84
DSM (prioritized on power saving)	91.23	90.84	90.04	89.11	89.01	88.61	80.47
DSM with load prediction (prioritized on power saving)	93.17	92.47	91.78	91.34	90.89	90.11	82.36
DSM (prioritized on performance)	96.14	95.67	94.89	94.17	93.56	92.99	84.38
DSM with load prediction (prioritized on performance)	98.47	97.87	97.14	96.37	95.94	95.46	87.14

of this gain is the proposed mechanism that can effectively reduce the transmission power of URLLC UEs, resulting in smaller interference to the eMBB services. When targeting at the URLLC performance, it can be seen that the DSM version prioritizing on performance and using load prediction provides the best performance. As indicated in Table 5, the percentage of URLLC UEs satisfying the requirements with the latter DSM version 6.5% and 14.3% larger than that with the ULCI and PC schemes, respectively. This witnesses that the proposed selection mechanism uses the two involved methods in a complementary way, implying that one method can be used when the other is not supported or cannot be used. Evidently, load prediction enables the gNB to take more timely and accurate resource allocation decisions.

5 Conclusion

In this paper, we presented novel resource allocation methods aiming to better balance the performance between eMBB and URLLC UEs within the same 5G cell, which are competing for the same set of time and frequency resources. A DPCI scheme including a 2-D bitmap resource indication and an ROPC scheme with dynamic power control was proposed, which was shown via system-level simulation to advance the existing resource allocation methods and improve the achievable performance. In addition, a DSM based on load prediction was proposed that renders the resource allocation scheme capable of adapting to different channel qualities, thus, further boosting the overall performance. Extensive system-level simulation results were presented, which showcased that the perceived throughput of eMBB UEs is increased by 45.3%, while about 13.3% more UEs are enjoying URLLC services with all them saving power of about 2.6 dB on average.

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