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Unlicensed Assisted Ultra-Reliable and Low-Latency Communications

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Abstract
The *ultra-reliable and low-latency communication* (URLLC) in the *fifth generation* (5G) communication has emerged many potential applications, which promotes the development of the *internet of things* (IoTs). In this paper, the URLLC system adopts the *duty-cycle muting* (DCM) mechanism to share unlicensed spectrums with the WiFi network, which guarantees the fair coexistence. Meanwhile, we use the mini-slot, user grouping, and finite block length regime to satisfy the low latency and high reliability requirements. We establish a non-convex optimization model with respect to power and spectrum, and solve it to minimize the power consumption at the devices, where the closed-form expressions are given by several mathematical derivations and the Lagrangian multiplier method. Numerical simulation results are provided to verify the feasibility and effectiveness of the proposed scheme, which improves the system spectrum efficiency and energy efficiency.

Keywords URLLC · unlicensed band · finite block length regime · spectrum allocation · power allocation

1 Introduction

The *Third Generation Partnership Project* (3GPP) *radio access network* (RAN) has officially released the *fifth generation* (5G) *new radio* (NR) standard firstly in 2017. Afterwards, the *International Telecommunication Union-Radiocommunication Sector* (ITU-R) has proposed three major application scenarios for 5G: the *enhanced mobile broadband* (eMBB) aspires to obtain higher transmission data rates; the *massive machine type communication* (mMTC) aims to provide massive connections for the *internet of things* (IoTs); the *ultra-reliable and low-latency communication* (URLLC) supports millisecond level low latency and ultra-reliable communications. In 4G *long term evolution* (LTE) mobile technology, the user plane delay is required to be less than 10 ms and the packet error rate is less than 10^{-2}, which means that, the reliability reaches 99%. However, according to the 3GPP standard [1], the URLLC requires the user plane delay of transmitting a 32-byte data packet is less than 1 ms and the block error rate is less than 10^{-5}, that is, the reliability reaches no less than 99.999%.

In recent years, with the promotion of Industry 4.0, URLLC has played a key role in applications such as industrial automation and *vehicle-to-vehicle* (V2V) communications. The study of low latency and high reliability for URLLC services mainly focuses on the utilization of licensed bands, which has been carried out on the *physical* (PHY) and *medium access control* (MAC) layers [2]. On one hand, in order to ensure strict low latency constraints, the *transmission time interval* (TTI) can be shortened. When the subcarrier spacing increases to 60 kHz, the TTI can contain 2 to 6 *orthogonal frequency division multiplexing* (OFDM) symbols [3]. A queuing mode of statistical multiplexing

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has been used to reduce the queuing delay [4]. Besides, the authors in [5, 6] have proposed the adaptive and dynamic hybrid automatic retransmission scheme to reduce the *hybrid automatic repeat request* (HARQ) delay. Moreover, non-orthogonal multiple access technology has been introduced to reduce transmission delay [7–9]. The use of novel channel coding methods allows parallel processing in the decoding process to reduce waiting time [10]. On the other hand, to achieve the stringent high reliability for URLLC, a finite block length regime has been adopted to shorten the transmission time [11]. Using frequency/space diversity technology can improve the reliability of wireless channels. In addition, packet replication has been exploited to improve the channel robustness [12]. Furthermore, employing multi-connection technology can achieve low latency and high reliability under different radio environments and network conditions [13, 14].

With the wide application of industrial automation, the limited channel capacity of the licensed bands causes the transmission congestion to URLLC traffic. Besides, factories need to pay operators to use the licensed bands, and require to meet strict low latency and high reliability constraints in URLLC services, which will bring large expenditure. Therefore, deploying URLLC on unlicensed bands has attracted tremendously attention. The unlicensed band contributes to increasing the network capacity, and facilitates the factory deployment of wireless devices. It also improves the factory cost-effectiveness due to its advantages of low cost, high flexibility, and a large quantity of the available bandwidth.

However, there are still some obstacles with URLLC accessing to the unlicensed channels. On one hand, URLLC devices access the licensed and unlicensed channels simultaneously, which will bring great challenges to achieve strict low latency. References [15, 16] have adopted a multi-channel multi-transmission mechanism to reduce channel access delay. The work in [17] has analyzed the *listen-before-talk* (LBT) mechanism and proposed a new channel access priority for URLLC services, which brings short transmission delay and guarantees the low latency constraint of 1 ms. The authors in [18] have proposed a wireless access technology based on MulteFire, which uses a grant-free uplink scheduling mechanism to reduce the uplink delay. At the same time, URLLC will be interfered with other wireless systems on unlicensed bands which reduces reliability. A hop-based multi-channel coordination mechanism uses busy tone and full-duplex radio technology to reduce interferences and collisions, which can meet URLLC high reliability requirements [19]. In [20], the authors have employed space diversity to send the same signal from different locations to obtain the maximum gain and improve the reliability of the wireless transmissions.

On the other hand, URLLC needs to consider fair coexistence with other wireless systems on unlicensed bands. Nowadays, the commonly used unlicensed bands are 2.4 GHz and 5 GHz. The 2.4 GHz spectrum is mainly used by ZigBee, Bluetooth, WiFi, and other wireless systems. The 5 GHz spectrum is mainly occupied by WiFi system. This paper considers the fair coexistence of the URLLC and WiFi systems. The deployment of the NR-U system in 5 GHz also follows the relevant regulations of *LTE on unlicensed band* (LTE-U) [16]. The commonly used LTE-U and WiFi coexistence mechanisms are the LBT and *duty-cycle muting* (DCM). We adopt the DCM to ensure the harmonious coexistence of the URLLC and WiFi systems.

Given the above investigations, unlicensed bands are complimentary to satisfy the URLLC transmission requirements, reduce the industrial costs, and increase the network capacity. In addition to ensure low latency and ultra-reliability, energy consumption should be considered as well. Since most of the devices are battery-powered, it is necessary to minimize the power consumption and extend the service life of the equipment. In this paper, a joint spectrum and power allocation scheme is proposed to minimize the total power consumption of the devices while meeting the strict low latency and high reliability requirements of URLLC transmission, when both licensed and unlicensed spectrums are available to the devices. In brief, the main contributions of this work are summarized as follows.

- We propose a scheme of spectrum and power resource allocation using the licensed and unlicensed bands. The URLLC system adopts the DCM to coexist with the WiFi system fairly on unlicensed bands. The unlicensed time fraction for URLLC is determined according to the estimated WiFi traffic load. The extra unlicensed spectrum resource is available to increase channel capacity and improve cost-effectiveness. Furthermore, we jointly adopt the DCM and OFDM technologies to make full use of time-frequency resources.
- We employ mini-slot frame structure and user grouping scheme to meet URLLC low latency requirement. At the same time, a finite block length regime is adopted to trade off the relationship between low latency, high reliability, and transmission data rate, which can guarantee the high reliability and improve the *spectrum efficiency* (SE).
- A power and spectrum optimization model is established to minimize the total power consumption at the devices, which meets the low latency, high reliability, and *quality of service* (QoS) constraints. However, the formulated optimization problem is non-convex. Fortunately, it can be converted into a convex optimization problem by variable substitution. Then, the closed-form solutions are derived by employing the Lagrangian multiplier method. Simulation results verify that the proposed

scheme effectively reduces the power consumption of the URLLC devices.

The rest of this paper is organized as follows. Section 2 introduces the system model. Then, we use the DCM mechanism to guarantee the fair coexistence of URLLC and WiFi systems. Moreover, the mini-slot, user grouping, and finite block length regime are adopted to satisfy low latency and high reliability. Meanwhile, we analyze the URLLC available transmission data rates. In Section 3, a joint spectrum and power allocation scheme on licensed and unlicensed bands is proposed. We also establish an optimization model for minimizing the total power consumption and propose a joint resource allocation optimization algorithm. Section 4 provides simulation results and performance analysis on the proposed scheme. Finally, we conclude the paper in Section 5.

2 System model

In this paper, the scenario where the NR-U cellular system uses both licensed and unlicensed spectrums to serve the URLLC devices is considered. As depicted in Fig. 1, a NR-U *base station* (BS) serves I URLLC devices which are denoted as a set of $\mathcal{U} = \{U_1, U_2, \cdots, U_i, \cdots, U_I\}$. In addition, there are K different unlicensed channels and each WiFi *access point* (AP) accesses an unlicensed channel, denoted as a set of $\mathcal{W} = \{W_1, W_2, \cdots, W_k, \cdots, W_K\}$, in the coverage of the BS. The BS adopts the DCM mechanism to ensure the fair coexistence with the WiFi system on unlicensed bands. The devices are in charge of sensing the unlicensed channels, estimating the WiFi traffic load, and feeding back information to the BS. Then, the BS decides the available time fractions on the corresponding unlicensed channels. Accordingly, the BS may use both licensed and unlicensed channels to provide the uplink transmission service for the URLLC devices. Moreover, on licensed spectrum, the OFDM technique is applied to divide the licensed bands into J subchannels with the same bandwidth.

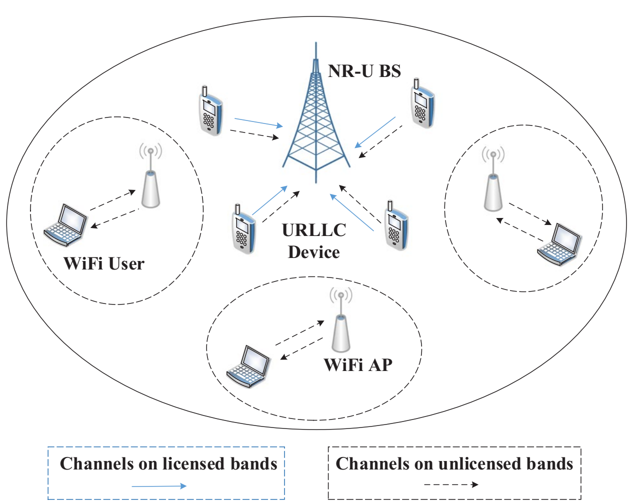


Fig. 1 A coexistence model between the URLLC and WiFi systems

2.1 Delay model and matency guarantee

According to the 3GPP standard [1], the user plane latency is defined as the time spent on successfully delivering an application layer packet/message from the 2/3 *service data unit* (SDU) ingress point to the 2/3 SDU egress point at the radio protocol layer, which is given by

$$T = T^{(qe)} + T^{(bp)} + T^{(fa)} + T^{(tx)} + T^{(mp)} + t \cdot T^{(rx)}, \tag{1}$$

where $T^{(qe)}$ represents the queuing delay for the data packets to wait for transmission in the buffer, which comes from the statistical multiplexing of multiple URLLC user data streams. $T^{(fa)}$ stands for the frame alignment delay, which is between 0 and TTI [21], and $T^{(tx)}$ is the transmission delay. $T^{(bp)}$ and $T^{(mp)}$ are defined as the processing delay at the BS and URLLC devices, respectively. In the 5G NR system, with the development of integrated circuits, the processing delay will be much less than a few milliseconds. Therefore, it is usually ignored for convenience [22, 23]. $T^{(rx)}$ indicates the retransmission delay, which allows devices and BS to use 3 symbols when the subcarrier spacing is between 15 and 30 kHz, and use 9 symbols when the subcarrier spacing is between 60 and 240 kHz. Besides, t is the number of retransmissions.

To meet the low latency requirement, user grouping scheme in [24] is applied while reducing the control signaling overheads, that is, we disperse a group of N users into M consecutive time slots. The number of users in a group can be expressed as

$$N = \sum_{m=1}^{M} N_m, \tag{2}$$

where N_m is the total number of active URLLC users in the m th $(1 \leq m \leq M)$ time slot.

2.2 Available unlicensed spectrum

To ensure the harmonious coexistence between the NR-U and WiFi systems, the DCM mechanism is adopted, where the devices turn transmission "on/off" on the unlicensed channels periodically. During the "off" period, the WiFi APs occupy the unlicensed channels to serve WiFi terminals while the devices implement the carrier sensing to estimate the WiFi traffic loads information and feed back it to the BS, as shown in Fig. 2. Besides, the BS optimizes spectrum

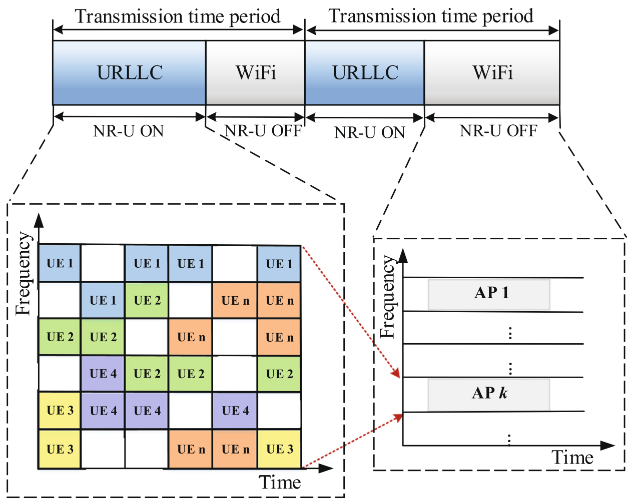


Fig. 2 The time-frequency resource allocation scheme

resource allocation for the URLLC devices during the "on" period. We divide time-frequency resources into multiple subcarriers. Multiple URLLC devices can transmit data on each time slot, and each URLLC device can occupy one or more subcarriers.

Based on [25], the WiFi traffic loads can be estimated accurately. Then, according to [26], the time fraction, $\theta_k^{(U)}$, available to the URLLC devices on unlicensed channel k can be expressed as

$$\theta_k^{(U)} \leq 1 - d_k^{(U)}, \tag{3}$$

where $d_k^{(U)}$ represents the time fraction occupied by the WiFi users on unlicensed channel k, defined as $d_k^{(U)} = \frac{\hat{R}_k^{(\max)}}{\hat{R}_k}$. Typically, $\hat{R}_k$ denotes the average WiFi throughput achieved on the unlicensed spectrums when $1 - \theta_k^{(U)}$ time fraction is used by the WiFi systems, $\hat{R}_k^{(\max)}$ accounts for the maximum achievable average throughput of WiFi system when there are only WiFi users using the unlicensed spectrums, $\theta_k^{(U)} \in [0, 1]$. Both $\hat{R}_k$ and $\hat{R}_k^{(\max)}$ can be achieved by the scheme used in [25].

We can obtain the $d_k^{(U)}$ available for WiFi users through the accurately estimated WiFi traffic loads. Then, we can dynamically adjust the unlicensed time fraction 1-$d_k^{(U)}$ occupied by the URLLC devices when adopting the DCM to access the unlicensed channels. So as to effectively use the unlicensed spectrum resources and improve the system performance while guaranteeing the fair coexistence of URLLC and WiFi systems.

2.3 Data rate analysis

Since the BS can not only use licensed spectrums but also share unlicensed spectrums with the WiFi network to serve the URLLC devices. The achievable data rates can be divided into two parts which include the data rates on licensed and unlicensed bands respectively. Moreover, to satisfy the low latency and high reliability requirements, finite data block length is employed in the URLLC system as described in [11, 27]. However, the finite data block length will bring about the loss on data rates and the Shannon channel capacity is no longer applicable [11, 27]. In order to meet the latency and reliability constraints while not sacrificing more data rates, it is necessary to trade off the relationship between the transmission data rate, the finite block length, and the transmission error probability.

According to the above analysis, the achievable uplink data rate of URLLC device i on licensed subchannel j is given by

$$R_{i,j}^{(L)} = \xi_{i,j}^{(L)} W^{(L)} \left(\log(1 + \gamma_{i,j}^{(L)}) - \sqrt{\frac{V_{i,j}^{(L)}}{l}} \frac{Q^{-1}(\varepsilon)}{\ln 2} \right), \tag{4}$$

where $\xi_{i,j}^{(L)}$ represents the fraction of the bandwidth allocated to device i on licensed subchannel j, $W^{(L)}$ is the licensed bandwidth, $\gamma_{i,j}^{(L)}$ stands for the *signal to interference plus noise ratio* (SINR) experienced at device i on licensed subchannel j, defined as $\gamma_{i,j}^{(L)} = \frac{p_{i,j}^{(L)} h_{i,j}^{(L)}}{\xi_{i,j}^{(L)} W^{(L)} N_0}$, $p_{i,j}^{(L)}$ is the transmission power of device i on licensed subchannel j, $h_{i,j}^{(L)}$ represents the channel power gain between the BS and device i on licensed subchannel j, N_0 is the noise power spectrum density of *additive white Gaussian noise* (AWGN). Besides, $V_{i,j}^{(L)}$ represents the channel dispersion of device i on licensed subchannel j, defined as $V_{i,j}^{(L)} = 1 - (1 + \gamma_{i,j}^{(L)})^{-2}$, $Q^{-1}(\varepsilon)$ remarks the inverse of complementary Gaussian cumulative distribution function, ε indicates the transmission error probability, $Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt$, and l reflects the block length. It is noteworthy that $V \approx 1$, when the SINR experienced on the channel is higher than 10 dB.

When transmitting on the unlicensed channels, the uplink data rate achieved at URLLC device i on unlicensed channel k can be expressed as

$$R_{i,k}^{(U)} = \theta_{i,k}^{(U)} W^{(U)} \left(\log(1 + \gamma_{i,k}^{(U)}) - \sqrt{\frac{V_{i,k}^{(U)}}{l}} \frac{Q^{-1}(\varepsilon)}{\ln 2} \right), \tag{5}$$

where $\theta_{i,k}^{(U)} \in [0, 1]$, is the time fraction allocated to device i on unlicensed channel k, $W^{(U)}$ is the unlicensed channel bandwidth, $\gamma_{i,k}^{(U)}$ is the SINR experience on unlicensed channel k of device i, defined as $\gamma_{i,k}^{(U)} = \frac{p_{i,k}^{(U)} h_{i,k}^{(U)}}{N_0 W^{(U)}}$, $p_{i,k}^{(U)}$ is the transmission power of device i on unlicensed channel k, $h_{i,k}^{(U)}$ represents the channel power gain between BS and device i on unlicensed channel k, $v_{i,k}^{(U)}$ is the channel dispersion of device i on unlicensed channel k, defined as $V_{i,k}^{(U)} = 1 - (1 + \gamma_{i,k}^{(U)})^{-2}$.

Based on the above analysis, the total achievable data rate at URLLC device i can be written as

$$R_i = \sum_{j=1}^{J} R_{i,j}^{(L)} + \sum_{k=1}^{K} R_{i,k}^{(U)}, \tag{6}$$

where $R_{i,j}^{(L)}$ and $R_{i,k}^{(U)}$ are expressed as Eqs. 4 and 5, respectively.

2.4 Power consumption

In general, the power consumption of each URLLC device mainly contains three parts. The first and second parts are the transmission power consumed by the device on licensed and unlicensed channels, respectively. The third part is the sensing power consumption on unlicensed channels at the device. Accordingly, the power consumption of URLLC device i can be expressed as

$$P_i = \sum_{j=1}^{J} p_{i,j}^{(L)} + \sum_{k=1}^{K} \theta_{i,k}^{(U)} p_{i,k}^{(U)} + \sum_{k=1}^{K} (1 - \theta_{i,k}^{(U)}) p_s^{(U)}, \tag{7}$$

where $p_s^{(U)}$ is the sensing power consumption on the unlicensed channel k, which is a constant. The first item is the power consumption of the device i on licensed channels and has no direct relation with unlicensed time fraction, $\theta_{i,k}^{(U)}$. The second and third items are the total power consumption of the device i on the unlicensed channels. They are affected by $\theta_{i,k}^{(U)}$.

The total power consumed by all URLLC devices containing licensed and unlicensed power consumption in the uplink transmission can be written as

$$P^{(tot)} = \sum_{i=1}^{N} P_i, \tag{8}$$

where P_i is given by Eq. 7.

3 Power consumption minimization

In this section, we first formulate a spectrum and power optimization problem. Due to the non-convexity of the objective function and constraint conditions of the optimization problem, the existing optimization tools cannot solve it directly. Therefore, the non-convex optimization problem needs to be converted into a convex optimization problem through form conversion. Then, the Lagrangian multiplier method is adopted to obtain the closed-form expressions on spectrum and power allocation. Finally, we provide the adaptive channel access algorithm in the coexistence of URLLC and WiFi systems.

3.1 Problem formulation

In consideration of the limited battery capacity of devices, our objective is to minimize the power consumption at the BS and devices while meeting the strict low latency and high reliability requirements. Accordingly, the optimization problem can be formulated as

$$P1: \min_{\{p_{i,j}^{(L)}, p_{i,k}^{(U)}, \xi_{i,j}^{(L)}, \theta_{i,k}^{(U)}, l\}} P^{(tot)}, \tag{9}$$

subject to

$$R_i \geqslant r, \ \forall i, \tag{9a}$$

$$\sum_{i=1}^{N} \xi_{i,j}^{(L)} \leqslant 1, \ \forall j, \tag{9b}$$

$$\sum_{i=1}^{N} \theta_{i,k}^{(U)} \leqslant 1 - d_k^{(U)}, \ \forall k, \tag{9c}$$

$$\sum_{i=1}^{N} \theta_{i,k}^{(U)} p_{i,k}^{(U)} \leqslant p_t^{(U)}, \ \forall k, \tag{9d}$$

$$\sum_{j=1}^{J} p_{i,j}^{(L)} + \sum_{k=1}^{K} \theta_{i,k}^{(U)} p_{i,k}^{(U)} + \sum_{k=1}^{K} (1 - \theta_{i,k}^{(U)}) p_s^{(U)} \leqslant P^{(max)}, \ \forall i, \tag{9e}$$

$$p_{i,j}^{(L)} \geqslant 0, p_{i,k}^{(U)} \geqslant 0, \xi_{i,j}^{(L)} \geqslant 0, \theta_{i,k}^{(U)} \geqslant 0, \ \forall i, j, k, \tag{9f}$$

where the objective function Eq. 9 aims to minimize the total power consumption, Eq. 9a is to satisfy the minimum transmission data rate requirements of each device to guarantee the QoS, Eq. 9b guarantees the allocated licensed spectrum bandwidth is less than $W^{(L)}$, Eq. 9c ensures that the allocated unlicensed spectrum is less than or equal to the available one, $\sum_{i=1}^{N} \theta_{i,k}^{(U)}$ is the time fraction allocated to the devices on the unlicensed channel k, Eq. 9d aims to limit the transmission power of the devices on the unlicensed channels, and Eq. 9e is the total power constraint of each device.

In order to obtain the optimal tradeoff between SE and *energy efficiency* (EE) of the URLLC system, we need to solve the problem $P1$ to find the optimal solutions of $p_{i,j}^{(L)}$, $p_{i,k}^{(U)}$, $\xi_{i,j}^{(L)}$, $\theta_{i,k}^{(U)}$, and l. Obviously, problem $P1$ is a non-convex optimization problem with the non-convex objective function Eq. 9, constraints Eqs. 9a, and 9e. The globally optimal solutions cannot be solved directly. To acquire the closed-form expressions of the problem, two steps are carried out. First, we assume that the block length l is known when solving the problem $P1$. However, problem $P1$ is still a non-convex problem with regard to $p_{i,j}^{(L)}$, $p_{i,k}^{(U)}$, $\xi_{i,j}^{(L)}$, and $\theta_{i,k}^{(U)}$. Let $A_{i,k}^{(U)} = \theta_{i,k}^{(U)} \cdot p_{i,k}^{(U)}$, problem $P1$ can be converted into a convex optimization problem with respect to $p_{i,j}^{(L)}$, $A_{i,k}^{(U)}$, $\xi_{i,j}^{(L)}$, and $\theta_{i,k}^{(U)}$ according to Appendix A. Then, we can acquire a optimal l by simulation.

3.2 Optimal allocation of power and spectrum

Based on the previous analysis, problem $P1$ is proved to be a convex optimization problem according to Appendix A. Then, we use the Lagrangian multiplier method to solve the problem and obtain the closed-form expressions of the globally optimal power and spectrum allocation. The SE and EE of the considered system can be further improved while minimizing the total power consumption. We provide the detailed solution process in the following. The constructed Lagrangian function can be written as

$$\begin{aligned} & f\left(p_{i,j}^{(L)}, A_{i,k}^{(U)}, \xi_{i,j}^{(L)}, \theta_{i,k}^{(U)}, \alpha_j, \beta_k, \psi_i, \mu_k, \lambda_i\right) \\ & = P^{(tot)} + \sum_{i=1}^{N} \lambda_i (r - R_i) \\ & + \sum_{j=1}^{J} \alpha_j \left(\sum_{i=1}^{N} \xi_{i,j}^{(L)} - 1 \right) + \sum_{k=1}^{K} \beta_k \left(\sum_{i=1}^{N} A_{i,k}^{(U)} - p_t^{(U)} \right) \\ & + \sum_{i=1}^{N} \psi_i \left(\sum_{j=1}^{J} p_{i,j}^{(L)} + \sum_{k=1}^{K} A_{i,k}^{(U)} + \sum_{k=1}^{K} (1 - \theta_{i,k}^{(U)}) p_s^{(U)} - P^{(max)} \right) \\ & + \sum_{k=1}^{K} \mu_k \left(\sum_{i=1}^{N} \theta_{i,k}^{(U)} - 1 + d_k^{(U)} \right), \end{aligned} \tag{10}$$

where λ_i, α_j, β_k, ψ_i, and μ_k are denoted as Lagrangian multipliers, respectively. And *Karush-Kuhn-Tucker* (KKT) conditions can be obtained as follows

$$\frac{\partial f}{\partial p_{i,j}^{(L)}} = 0, \ \forall i, j, \tag{11}$$

$$\frac{\partial f}{\partial A_{i,k}^{(U)}} = 0, \ \forall i, k, \tag{12}$$

$$\frac{\partial f}{\partial \xi_{i,j}^{(L)}} = 0, \ \forall i, j, \tag{13}$$

$$\frac{\partial f}{\partial \theta_{i,k}^{(U)}} = 0, \ \forall i, k, \tag{14}$$

$$\lambda_i (r - R_i) = 0, \ \forall i, \tag{15}$$

$$\alpha_j \left(\sum_{i=1}^{N} \xi_{i,j}^{(L)} - 1 \right) = 0, \ \forall j, \tag{16}$$

$$\beta_k \left(\sum_{i=1}^{N} A_{i,k}^{(U)} - p_t^{(U)} \right) = 0, \ \forall k, \tag{17}$$

$$\psi_i \left(\sum_{j=1}^{J} p_{i,j}^{(L)} + \sum_{k=1}^{K} A_{i,k}^{(U)} + \sum_{k=1}^{K} (1 - \theta_{i,k}^{(U)}) p_s^{(U)} - P^{(max)} \right) = 0, \ \forall i, \tag{18}$$

$$\mu_k \left(\sum_{i=1}^{N} \theta_{i,k}^{(U)} - 1 + d_k^{(U)} \right) = 0, \ \forall k, \tag{19}$$

$$\lambda_i \geq 0, \alpha_j \geq 0, \beta_k \geq 0, \psi_i \geq 0, \mu_k \geq 0, \ \forall i, j, k. \tag{20}$$

Based on the KKT conditions, we can derive the globally optimal solutions of the spectrum and power allocation for URLLC device i on licensed and unlicensed channels. The closed-form expressions are written as follows

$$p_{i,j}^{(L)} = \xi_{i,j}^{(L)} W^{(L)} \left(\frac{\lambda_i}{\psi_i} - \frac{N_0}{h_{i,j}^{(L)}} \right)^+, \tag{21}$$

$$A_{i,k}^{(U)} = \theta_{i,k}^{(U)} W^{(U)} \left(\frac{\lambda_i}{\beta_k + \psi_i} - \frac{N_0}{h_{i,k}^{(U)}} \right)^+, \tag{22}$$

$$\xi_{i,j}^{(L)} = \frac{\lambda_i R_{i,j}^{(L)} - \psi_i p_{i,j}^{(L)}}{\alpha_j}, \tag{23}$$

$$\theta_{i,k}^{(U)} = \frac{\lambda_i R_{i,k}^{(U)} - (\beta_k + \psi_i) A_{i,k}^{(U)}}{\mu_k - \psi_i p_s^{(U)} - p_s^{(U)}}. \tag{24}$$

By defining $A_{i,k}^{(U)} = \theta_{i,k}^{(U)} \cdot p_{i,k}^{(U)}$, the optimal spectrum and power allocations of device i on unlicensed channel k can be respectively expressed as

$$p_{i,k}^{(U)} = W^{(U)} \left(\frac{\lambda_i}{\beta_k + \psi_i} - \frac{N_0}{h_{i,k}^{(U)}} \right)^+, \tag{25}$$

$$\theta_{i,k}^{(U)} = \frac{\lambda_i R_{i,k}^{(U)}}{\mu_k - \psi_i p_s^{(U)} - p_s^{(U)} + (\beta_k + \psi_i) A_{i,k}^{(U)}}, \tag{26}$$

where $(a)^+$ represents $\max(a, 0)$, α_j and μ_k are the Lagrangian multipliers of the constraints Eqs. 9b and 9c on licensed and unlicensed spectrum restrictions respectively, β_k and ψ_i are the Lagrangian multipliers of the unlicensed power limitation and total power limitation of the constraints Eqs. 9d and 9e, respectively. We can see that the closed-form expressions of $p_{i,j}^{(L)}$ and $p_{i,k}^{(U)}$ are similar to the power allocation of the water-filling algorithm. It is clearly that $p_{i,j}^{(L)}$ is related to $\xi_{i,j}^{(L)}$, and $p_{i,k}^{(U)}$ is also related to $\theta_{i,k}^{(U)}$ according to Eqs. 24 and 25.

3.3 Optimal algorithm development

Based on the aforementioned analysis, the details to solve the optimization problem $P1$ can be summarized in Algorithm 1. Firstly, according to Eq. 3, we can estimate the WiFi traffic load by the number of WiFi users and calculate the time fraction on unlicensed channels $1-d_k^{(U)}$ for URLLC devices. Next, according to Eqs. 21, 23, 25, and 26, the Lagrangian multiplier method is adopted to obtain the globally optimal solutions of the problem $P1$. Thus, we can acquire the globally optimal allocations of power and spectrum for URLLC devices on licensed and unlicensed bands.

Algorithm 1 Adaptive channel access algorithm in the coexistence of URLLC and WiFi systems.

Initialize : NR-U BS determines the available licensed bandwidth fraction $\xi_{i,j}^{(L)}$, obtains the available unlicensed time fraction $1-d_k^{(U)}$, initializes block length l.
if $1-d_k^{(U)}=0$ **then**
  The URLLC system only accesses licensed channels, and obtains the optimal solutions of $p_{i,j}^{(L)}$ and $\xi_{i,j}^{(L)}$ according to Eqs. 21 and 23.
else if $0<1-d_k^{(U)}<1$ **then**
  The URLLC system simultaneously accesses licensed and unlicensed channels.
  According to Eqs. 21, 23, 25, and 26, get the optimal solutions of $p_{i,j}^{(L)}$, $\xi_{i,j}^{(L)}$, $p_{i,k}^{(U)}$, and $\theta_{i,k}^{(U)}$.
else
  The URLLC system only accesses unlicensed channels, and acquires the optimal solutions of $p_{i,k}^{(U)}$ and $\theta_{i,k}^{(U)}$ according to Eqs. 25 and 26.
end if
return the globally optimal solution $P=\{p_{i,j}^{(L)},\xi_{i,j}^{(L)},p_{i,k}^{(U)},\theta_{i,k}^{(U)}\}$, $\forall i,j,k$.

4 Simulation results and discussion

In this section, we provide numerical simulation results to verify the feasibility and effectiveness of the proposed URLLC power and spectrum allocation scheme for jointly licensed and unlicensed bands. We first evaluate the performance of the URLLC system. Next, we analyze the effect of unlicensed time fractions on joint resource allocation scheme. Finally, we analyze the impact of joint resource allocation scheme on licensed bands.

In the simulation scenario, we consider a URLLC network with a BS. There exist I URLLC devices randomly distributed within 50 meters coverage of BS, and the arrival of user data packets obeys a Poisson distribution. The mini-slot frame structure is adopted with the subcarrier of 30 kHz and 2 symbols. Meanwhile, we estimate the WiFi traffic load to calculate time fraction based on the number of WiFi users accessing the unlicensed channels. In addition, the licensed and unlicensed bandwidths are both 20 MHz. The licensed and unlicensed channels are Rayleigh fading channels. Unless otherwise specified, the simulation parameters are listed in Table 1.

Table 1 Simulation parameters

Parameters	Value
Maximum transmission power of each device, $P^{(max)}$	33 dBm
Transmission power on unlicensed band, $p_t^{(U)}$	23 dBm
AWGN noise power	-95 dBm (over 20 MHz BW)
Bandwidth on licensed and unlicensed bands, $W^{(L)}$, $W^{(U)}$	20 MHz
Path loss model on licensed band (dB)	$-15.3-37.6\log_{10}(d(m))$
Path loss model on unlicensed band (dB)	$-15.3-50\log_{10}(d(m))$
Maximum allowed transmission error probability, ε	10^{-5}
Delay requirement for URLLC	1 ms

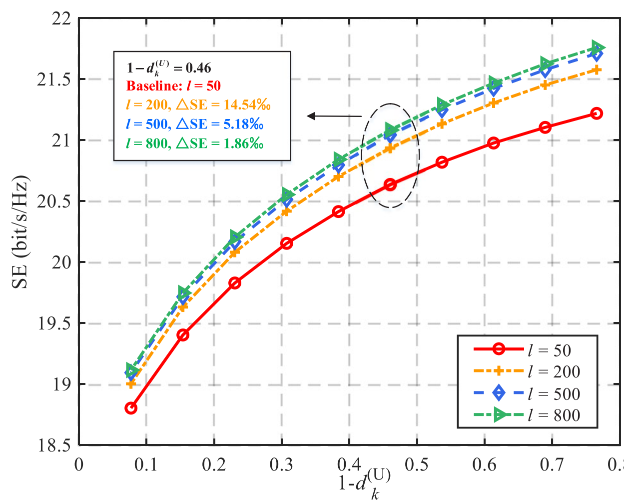


Fig. 3 The SE with different data block lengths and unlicensed time fractions

4.1 Optimize the URLLC system performance

Figure 3 depicts the achievable SE of the URLLC system with different time fractions on each unlicensed channel,

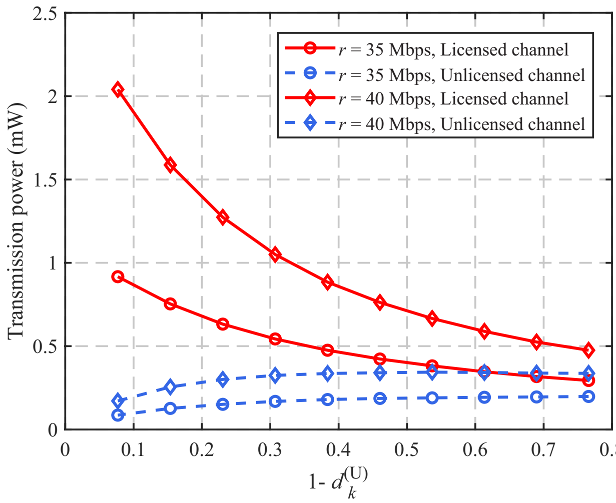


Fig. 4 The power consumption on licensed and unlicensed channels

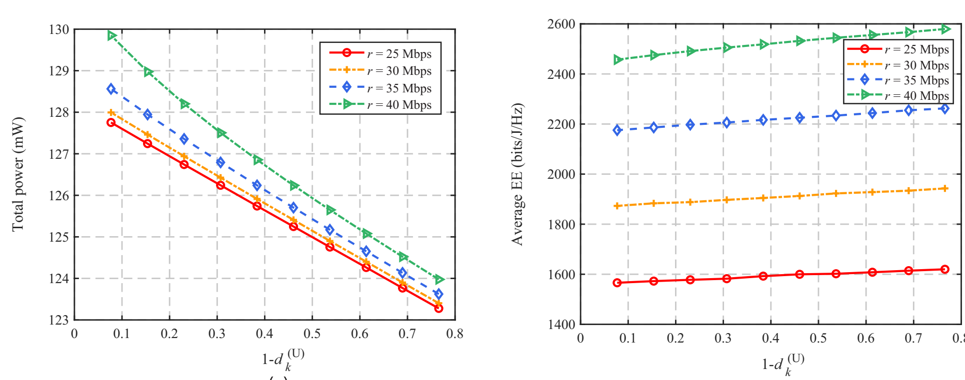
$1-d_k^{(U)}$, and data block length, with l= 50, 200, 500, and 800. As $1-d_k^{(U)}$ increases, the system SE increases as well. Therefore, the more opportunities the system has to use the unlicensed spectrum resources, the higher SE the system can achieve. Besides, as l increases, the proportion of control signaling overhead is reduced and the effective data information is increased, which would improve the SE.

However, when l increases to 500, if continuing to increase l, the SE improves only a little. We define a SE growth rate with $l = 50$ as the baseline, $\triangle SE = \frac{SE-SE_{50}}{SE_{50}}$. When $1-d_k^{(U)}$ is about 0.46 and l increases from 50 to 200, the SE improves 14.54‰. Then, when l increases from 200 to 500, the SE improves 5.18‰. When l increases from 500 to 800, the SE only improves 1.86‰. It is because that l is related to the transmission delay D_t and bandwidth W as follows, $l = D_tW$ [27]. If continuing to increase l, it will bring more transmission delay or require more bandwidth. Thus, we compromise the transmission delay, bandwidth, and data rate of the URLLC system. It can be seen that l = 500 is the optimal block length in this simulation. Therefore, l is selected to be 500 for the subsequent simulation analysis of the optimal power and spectrum allocation.

Figure 4 shows the impact of the available unlicensed spectrum resources on the system transmission power consumption. From the figure, when $1-d_k^{(U)}$ approaches 0, there are few available unlicensed spectrum resources and the URLLC devices mainly transmit data on licensed channels. More transmission power needs to be consumed on licensed channels while the transmission power consumption on unlicensed channels tends to 0. The licensed transmission power decreases while the unlicensed transmission power increases gradually with the increase of $1-d_k^{(U)}$. When the available unlicensed spectrum resources are sufficient, the transmission power consumption on licensed and unlicensed channels changes smoothly. Therefore, as the increase on the available unlicensed spectrums, there will have more freedom to save the transmission power. From the figure, we can also see that the transmission power consumption on licensed and unlicensed channels increases at high data rate, which guarantees the QoS for the URLLC system.

Figure 5a demonstrates the total power consumption with different time fractions and required minimum data rates, with $r = 25$, 30, 35, and 40 Mbps. The increase on $1-d_k^{(U)}$ implies that more unlicensed spectrum resources are available for the URLLC devices. Therefore, the power consumption for sensing the unlicensed channels to estimate the WiFi traffic loads decreases. In addition, Algorithm 1 optimizes the power and spectrum allocation, which can further reduce the total power consumption.

However, as r increases, more transmission power is required to meet the increase on the data rate requirements. Moreover, with the increase of $1-d_k^{(U)}$, the gap of total power consumption under different r gradually decreases. It is mainly because that the transmission



(a) (b)

Fig. 5 The total power consumption and EE with different time fractions and minimum data rates. **a** The total power consumption, (**b**) The average EE

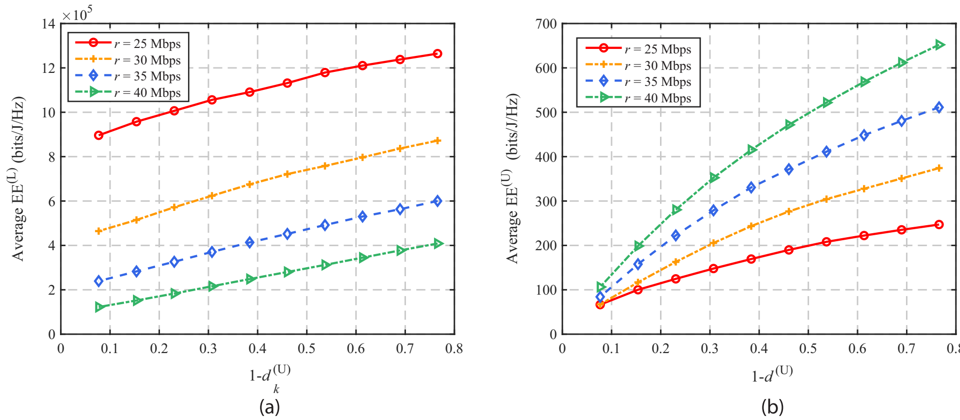


Fig. 6 The average EE with different time fractions and minimum data rate requirements. **a** The average EE on licensed bands, (**b**) The average EE on unlicensed bands

power consumed on licensed channels and sensing power consumed on unlicensed channels decrease. When $1-d_k^{(U)}$ is higher than 0.7, the available unlicensed spectrums are sufficient and the sensing power consumption is small. The transmission power consumption on licensed and unlicensed channels tends to be stable. Therefore, the total power consumption gap under different r is almost unchanged.

Similarly, Fig. 5b depicts the average system EE with different available time fractions on unlicensed channels and minimum data rate requirements. As $1-d_k^{(U)}$ increases, the average EE increases as well. Moreover, Algorithm 1 can effectively decrease the total system power consumption. Besides, the average EE also improves as r increases.

4.2 Impact of the available unlicensed spectrum

Figure 6a shows the effect of Algorithm 1 on the EE achieved on licensed channels. When the available unlicensed spectrum resources increase, the URLLC devices can release the pressure on licensed spectrum by using unlicensed channels, and acquire more channel capacity. Therefore, the devices can use the licensed spectrums more efficiently by Algorithm 1 to improve the EE on licensed channels. On the contrary, as r increases, in order to satisfy the high data rate requirements, the power consumption increases and the average EE decreases.

Figure 6b demonstrates the impact of Algorithm 1 on EE achieved on unlicensed channels. When the available unlicensed spectrum resources are close to 0, the EE achieved on unlicensed channels with different data rate requirements tends to 0. When $1-d_k^{(U)}$ increases, the EE on unlicensed channels increases. Different from the EE achieved on licensed channels, the EE increases when r increases. It is because the available unlicensed spectrum resources increase as the increase on the data rate requirements of devices. Therefore, there is more freedom in frequency domain to decrease the power consumption by the proposed scheme.

It is noteworthy that the average EE on unlicensed bands is generally lower than that of the licensed bands, as demonstrated in Fig. 6a and b. This is because that the power consumption on unlicensed channels including the transmission power and sensing power, which is greater than power consumed on licensed channels. Thus, the unlicensed average EE is lower.

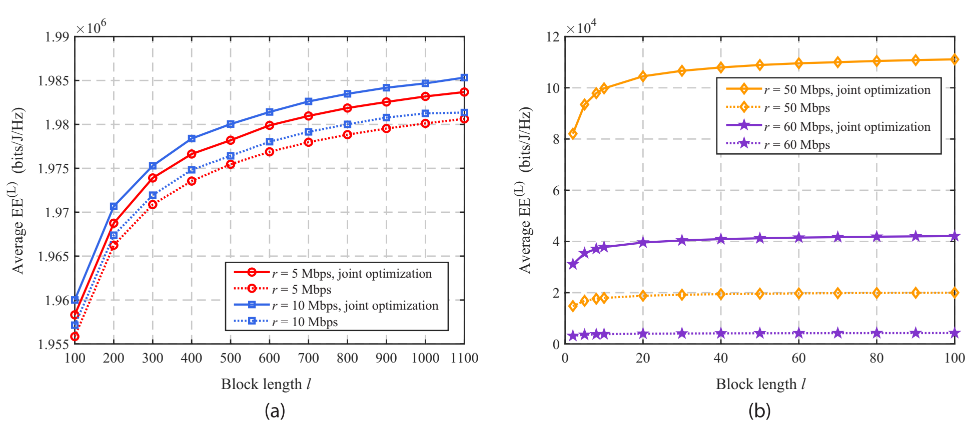


Fig. 7 The average EE with different data block lengths and minimum data rates. **a** $r=$ 5 Mbps, 10 Mbps, (**b**) r = 50 Mbps, 60 Mbps

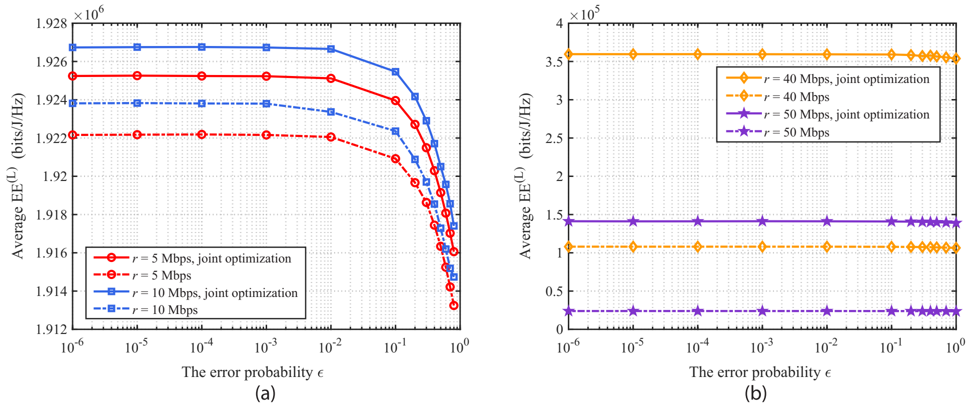


Fig. 8 The average EE with different error probabilities and minimum data rates. **a** r = 5 Mbps, 10 Mbps, (**b**) r = 40 Mbps, 50 Mbps

4.3 Impact of resource allocation scheme on licensed bands

Figure 7 compares the achievable EE on the licensed channels with different data block lengths and minimum data rate requirements when Algorithm 1 and the conventional scheme are adopted. In both schemes, as l increases, the system EE increases as well. Figure 8 compares the variation of the average EE on licensed bands with different transmission error probabilities and the minimum data rate requirements. The system EE on licensed channels decreases as the error probability increases.

From Figs. 7 and 8, we can observe that the system EE of Algorithm 1 is higher than that of the conventional scheme. When r increases from 5 to 50 Mbps, Algorithm 1 can effectively decrease the power consumption on licensed channels. However, the conventional scheme dose not use the power and spectrum resource effectively. Therefore, it would consume more power and its achievable EE is lower. Moreover, when r increases, the power consumption by both schemes increases. In consequence, the EE may decrease.

5 Conclusion

In this paper, in order to release the pressure of using the licensed bands and reduce power consumption of the devices, we propose an optimal spectrum and power allocation scheme for unlicensed assisted URLLC system. The DCM is adopted to guarantee the harmonious coexistence with the WiFi system. Meanwhile, we use the mini-slot and user grouping to meet the strict low latency. A finite block length regime is also employed to balance the transmission data rate, block length, and transmission error probability. We also formulate a non-convex optimization problem to minimize the power consumption, which satisfies the low latency and high reliability requirements. Then, several mathematical derivations and the Lagrangian multiplier method are applied to convert it into a convex optimization problem and derive globally optimal solutions on power and spectrum allocation. Simulation results are presented to verify that the proposed scheme effectively saves energy and improves the SE and EE for the URLLC system.

Appendix A: Proof of convexity

The objective function Eq. 9 includes three parts. We can replace the second part, $\theta_{i,k}^{(U)}$ and $p_{i,k}^{(U)}$, with $A_{i,k}^{(U)}$. And $P^{(tot)}$ can be written as

$$P^{(tot)} = \sum_{i=1}^{N}\sum_{j=1}^{J} p_{i,j}^{(L)} + \sum_{i=1}^{N}\sum_{k=1}^{K} A_{i,k}^{(U)} + \sum_{i=1}^{N}\sum_{k=1}^{K}(1-\theta_{i,k}^{(U)})p_s^{(U)}. \tag{A1}$$

Therefore, the objection function is a linear and convex function with respect to $p_{i,j}^{(L)}$, $A_{i,k}^{(U)}$, and $\theta_{i,k}^{(U)}$. The data rate of the URLLC device i on licensed subchannel j can be written as

$$R_{i,j}^{(L)} = \underbrace{\xi_{i,j}^{(L)} W^{(L)} \log\left(1 + \frac{p_{i,j}^{(L)} h_{i,j}^{(L)}}{\xi_{i,j}^{(L)} W^{(L)} N_0}\right)}_{C_1} \underbrace{- \xi_{i,j}^{(L)} W^{(L)} \sqrt{\frac{V_{i,j}^{(L)}}{l}} \frac{Q^{-1}(\epsilon)}{\ln 2}}_{C_2}, \tag{A2}$$

we can divide $R_{i,j}^{(L)}$ into two parts, denoted as C_1 and C_2. For the first part, in order to prove its convexity, we define a function

$$R_1(x,y) = -x\log\left(1+\frac{y}{x}\right), \tag{A3}$$

the Hessian matrix of $R_1(x,y)$ can be derived as

$$H = \begin{vmatrix} \frac{y^2/x}{(x+y)^2} & -\frac{y}{(x+y)^2} \\ -\frac{y}{(x+y)^2} & \frac{x}{(x+y)^2} \end{vmatrix}, \tag{A4}$$

which has two eigenvalues

$$\lambda_1 = 0,\ \lambda_2 = \frac{x^2 + y^2}{x^3 + 2x^2y + xy^2}. \tag{A5}$$

It is obvious that two eigenvalues are greater or equal to zero when $x \geq 0$. Thus, the function $R_1(x,y)$ is a convex function when $x \geq 0$. For the second part, when the SINR is greater than 10 dB, $V_{i,j}^{(L)}$ is approximately equal to 1. Therefore, the second part can be written as

$$C_2 = \xi_{i,j}^{(L)} W^{(L)} \sqrt{\frac{1}{l}} \frac{Q^{-1}(\varepsilon)}{\ln 2}, \tag{A6}$$

which is linear with respect to $\xi_{i,j}^{(L)}$. Then, $R_{i,j}^{(L)}$ can be rewritten as

$$\hat{R}_{i,j}^{(L)} = -f\left(\xi_{i,j}^{(L)} W^{(L)}, \frac{p_{i,j}^{(L)} h_{i,j}^{(L)}}{N_0}\right) - \xi_{i,j}^{(L)} W^{(L)} \sqrt{\frac{1}{l}} \frac{Q^{-1}(\varepsilon)}{\ln 2}, \tag{A7}$$

the combination of a concave function and a linear function is also a concave function. The data rate of the URLLC device i on unlicensed channel k can be expressed as

$$\begin{aligned} R_{i,k}^{(U)} &= \theta_{i,k}^{(U)} W^{(U)} \log\left(1 + \frac{p_{i,k}^{(U)} h_{i,k}^{(U)}}{N_0 W^{(U)}}\right) \\ &\quad - \theta_{i,k}^{(U)} W^{(U)} \sqrt{\frac{V_{i,k}^{(U)}}{l}} \frac{Q^{-1}(\varepsilon)}{\ln 2}, \end{aligned} \tag{A8}$$

let $A_{i,k}^{(U)} = \theta_{i,k}^{(U)} \cdot p_{i,k}^{(U)}$, and $R_{i,k}^{(U)}$ can be expressed as

$$\begin{aligned} R_{i,k}^{(U)} &= \theta_{i,k}^{(U)} W^{(U)} \log\left(1 + \frac{A_{i,k}^{(U)} h_{i,k}^{(U)}}{\theta_{i,k}^{(U)} N_0 W^{(U)}}\right) \\ &\quad - \theta_{i,k}^{(U)} W^{(U)} \sqrt{\frac{V_{i,k}^{(U)}}{l}} \frac{Q^{-1}(\varepsilon)}{\ln 2}, \end{aligned} \tag{A9}$$

we can prove $R_{i,k}^{(U)}$ is also a concave function in the same way as $R_{i,j}^{(L)}$. The data rate of the URLLC device i can be written as

$$R_i = \sum_{j=1}^{J} R_{i,j}^{(L)} + \sum_{k=1}^{K} R_{i,k}^{(U)}, \tag{A10}$$

the combination of a concave function and a concave function is also a concave function. In brief, problem $P1$ is a convex optimization problem.

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