Unlicensed Assisted Ultra-Reliable and Low-Latency Transmission

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Abstract. The *ultra-reliable and low-latency communication* (URLLC) has many potential applications in the *Internet of Things* (IoTs). This paper exploits both the licensed and unlicensed spectrums to support the URLLC transmissions, alleviating the lack of licensed spectrum resources, and adopts the *duty-cycle muting* (DCM) to ensure fair coexistence with the WiFi network. The user grouping scheme, mini-slot frame structure, and finite block length regime are used to guarantee low latency and high reliability. Meanwhile, to reduce the power consumption at the URLLC devices, we establish a minimum power optimization model and provide the globally optimal solutions. Simulation results are presented to verify the feasibility and effectiveness of the proposed scheme, which can not only reduce the power consumption at the devices, but also improve the system spectrum efficiency.

Keywords: URLLC · Finite block length regime · Unlicensed band · DCM · Spectrum allocation · Power allocation

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1 Introduction

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 millions of connections for the *Internet of Things* (IoTs), and the *ultra-reliable and low-latency communication* (URLLC) supports millisecond level low latency and ultra-reliable communications.

According to the 3GPP standard [1], URLLC requires the user plane delay of transmitting a 32-byte data packet to be less than 1 ms and requests the block error rate to be less than 10^{-5}, that is, the reliability reaches no less than 99.999%. However, in 4G *long term evolution* (LTE) technology, the user plane delay is required to be less than 10 ms and the packet error rate is less than 10^{-2}, that is, the reliability reaches 99%. Due to the strict latency and reliability conditions of URLLC, URLLC is applied to critical communication scenarios. The main potential applications include [2,3]:

- Emergency communication: remote diagnosis, remote surgery.
- Industrial automation: factory automation, smart grid, automatically distribute power grid energy, detect and restore grid faults.
- Intelligent transportation: intelligent transportation systems, autonomous driving, and *vehicle-to-vehicle* (V2V).
- Other applications: augmented reality and virtual reality.

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

However, there exist some problems with URLLC accessing the unlicensed bands, and there are a few researches of URLLC on unlicensed band currently. Due to the discontinuity of the unlicensed bands, which will bring challenges to achieve strict low latency conditions for URLLC. A multi-channel multi-transmission mechanism has been adopted to reduce channel access delay [4,5]. A new channel access priority has been proposed for URLLC services in the *listen-before-talk* (LBT) mechanism, which guarantees the low latency constraint of 1 ms [6]. The authors in [7] have proposed a wireless access technology based on MulteFire which uses a grant-free uplink scheduling mechanism to reduce the uplink delay. Besides, the URLLC system needs to consider fair coexistence with other wireless systems on unlicensed band. So that URLLC can reduce interference to other systems and improve its reliability. Nowadays, the commonly used unlicensed bands are 2.4 GHz and 5 GHz, which deploy WiFi, ZigBee, Bluetooth, and other wireless systems. We mainly consider the fair coexistence of URLLC and WiFi systems. Since the 5G NR estimates that it is essentially an extension of 4G LTE [5], the deployment of the NR-U in 5 GHz also follows the relevant regulations of LTE-U. The commonly used LTE-U and WiFi coexistence mechanisms are the LBT and *duty-cycle muting* (DCM). We adopt the DCM to guarantee the harmonious coexistence between URLLC and WiFi system.

In this paper, the URLLC system uses the unlicensed bands to reduce costs and increase network capacity. Since most of the terminal devices are battery-powered, it is necessary to minimize the power consumption of the transmitters and extend the service life of the devices. Therefore, our goal is to propose a spectrum and power resource allocation scheme for joint licensed and unlicensed bands to improve *spectrum efficiency* (SE) and *energy efficiency* (EE). We focus on minimizing total power consumption while satisfying the strict latency and reliability requirements. Firstly, the DCM mechanism is adopted to access unlicensed bands and ensure fair coexistence with URLLC and WiFi systems. Based on the estimated WiFi traffic loads, we can calculate the unlicensed time fraction for URLLC. Then, we employ the user grouping scheme and mini-slot frame structure to meet low latency requirement. We also establish an optimal power allocation model to minimize the total power consumption. Finally, the Lagrangian multiplier method is used to acquire the globally optimal solutions of the spectrum and power allocation. Simulation results verify that the proposed scheme effectively improves the SE and EE of the URLLC system.

The rest of this paper is organized as follows. In Sect. 2, we first introduce the system model and delay model. Then, the DCM mechanism is used to ensure fair coexistence between the URLLC and WiFi system. The user grouping scheme, mini-slot frame structure, and finite block length regime are adopted to guarantee low latency and high reliability. Meanwhile, we analyze the URLLC available transmission data rates. In Sect. 3, a minimum power optimization model is established. We propose an optimization algorithm for spectrum and power allocation. In Sect. 4, simulation results and performance analysis of the proposed scheme are provided. Finally, this paper is concluded in Sect. 5.

2 System Model

In the paper, the scenario where the NR-U cellular systems use both licensed and unlicensed spectrums to serve URLLC devices is studied. 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 WiFi *access points* (APs) using K different unlicensed channels, denoted as a set of $\mathcal{W} = \{W_1, W_2, \cdots, W_k, \cdots W_K\}$, in the coverage of the BS. 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 fraction on the corresponding unlicensed channels and adopts the DCM mechanism to share the unlicensed spectrum with the WiFi APs. Accordingly, the BS may use both licensed and unlicensed channels to serve the uplink transmission for URLLC devices. Moreover, on licensed spectrum, the OFDM technique is applied to divide the licensed bands into J subchannels which have the same bandwidth.

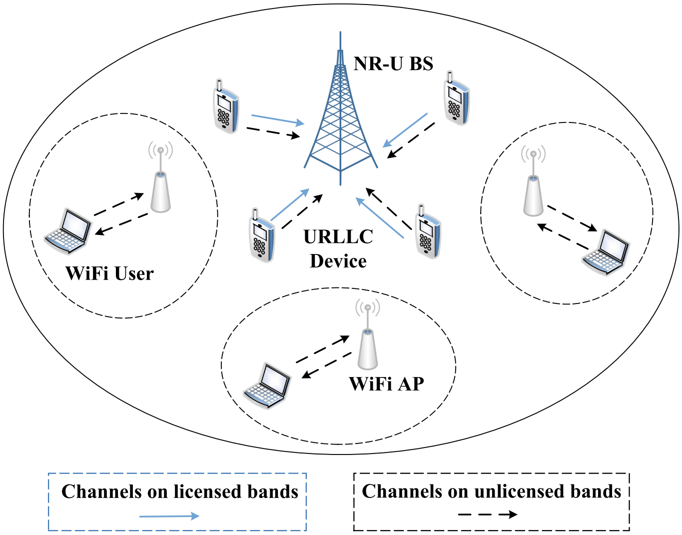

Fig. 1. A coexistence model between the URLLC and WiFi system.

2.1 Delay Model and Latency 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 radio protocol layer 2/3 *service data unit* (SDU) ingress point to the radio protocol layer 2/3 SDU egress point via the radio interface in both uplink and downlink directions, 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. $T^{(fa)}$ stands for the frame alignment delay which is between 0 and TTI [8], and $T^{(tx)}$ is the transmission delay. $T^{(bp)}$ and $T^{(mp)}$ are defined as the processing delay at the BS and the 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 can be ignored [9,10]. $T^{(rx)}$ represents the retransmission delay, which allows devices and the 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, t is the number of retransmissions.

To meet the low latency requirement, the user grouping scheme in [11] 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 devices in the mth $(1 \leq m \leq M)$ time slot.

2.2 Available Unlicensed Spectrum

To ensure the harmonious coexistence between the NR-U and WiFi system on unlicensed band, the DCM mechanism is adopted at the NR-U, where the NR-U turns "on/off" periodically. During the off period, the WiFi APs occupy the unlicensed channels to serve WiFi terminals while the NR-U implementing carrier sensing to estimate the WiFi traffic loads and decide the available time fraction on unlicensed channels.

Based on [12], the WiFi traffic loads can be estimated accurately. Then, according to [13], the time fraction, $\theta_k^{(U)}$, is 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 $d_k^{(U)} = \frac{\hat{R}_k^{(\max)}}{\hat{R}_k}$, $\hat{R}_k$ stands for the average WiFi throughput achieved on the unlicensed spectrum when $1 - \theta_k^{(U)}$ time fraction on the unlicensed spectrum is used by the WiFi systems, $\hat{R}_k^{(\max)}$ indicates the maximum achievable average throughput of the WiFi system when there are only WiFi users using the unlicensed spectrum, $\theta_k^{(U)} \in [0, 1]$. Both $\hat{R}_k$ and $\hat{R}_k^{(\max)}$ can be achieved by the scheme used in [12].

2.3 Data Rates Analysis

Since the URLLC devices can use licensed spectrum and share unlicensed spectrum with the WiFi network, the achievable data rates can be divided into two parts, including the data rates on licensed and unlicensed spectrums. Moreover, to satisfy the low latency and high reliability requirements, the finite data block length is employed in the URLLC system as described in [14,15]. However, the finite data block length will bring about the loss on data rates and the Shannon channel capacity is no longer applicable. In order to meet the latency and reliability constraints while satisfying minimum data rate, 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 data rates 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 bandwidth fraction 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* (SINR) experienced at the 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 allocated to the device i on licensed subchannel j, $h_{i,j}^{(L)}$ indicates 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), $V_{i,j}^{(L)}$ stands for the channel dispersion of device i on licensed subchannel j, defined as $V_{i,j}^{(L)} = 1-(1+\gamma_{i,j}^{(L)})^{-2}$, $Q^{-1}(\varepsilon)$ represents the inverse of complementary Gaussian cumulative distribution function, ε is the transmission error probability, $Q(x) = \int_x^{\infty} \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt$, l is the block length. It is noteworthy that $V \approx 1$, when the SINR experienced on the channel is higher than 10 dB.

When the BS transmits on the unlicensed channels, the downlink data rates of the 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 $\theta_{i,k}^{(U)} \in [0,1]$, represents the time fraction allocated to device i on unlicensed channel k, $W^{(U)}$ is the unlicensed channel bandwidth, $\gamma_{i,k}^{(U)}$ stands for the SINR experience on unlicensed channel k of device i, defined as $\gamma_{i,k}^{(U)} = \frac{p_{i,k}^{(U)} h_{i,k}^{(U)}}{N_0 W^{(U)}}$, $p_{i,k}^{(U)}$ indicates the transmission power allocated to i on unlicensed channel k, $h_{i,k}^{(U)}$ is the channel power gain between BS and device i on unlicensed channel k, $V_{i,k}^{(U)}$ stands for 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 rates at URLLC device i can be expressed as

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

2.4 Power Consumption

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 power consumed on sensing the unlicensed channel k, which is a constant.

The total power consumed by the URLLC devices in the uplink transmission can be written as

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

3 Power Consumption Minimization

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

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

subject to

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

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

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

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

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

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

where the objective function (9) aims to minimize the total power consumption, constraint (9a) is to satisfy the minimum transmission data rate requirements of each device to guarantee the QoS, constraint (9b) guarantees the allocated licensed spectrum bandwidth is less than $W^{(L)}$, (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, (9d) is to limit the transmission power of the devices on the unlicensed channels, (9e) is the total power constraint of each device.

3.1 Joint Power and Spectrum Allocation

Obviously, problem (9) is a non-convex optimization problem. Let $A_{i,k}^{(U)} = \theta_{i,k}^{(U)} \cdot p_{i,k}^{(U)}$, the objective function and constraint (9a) can be converted into convex functions through mathematical derivation. Accordingly, problem (9) can be converted into a convex optimization problem with respect to $p_{i,j}^{(L)}$, $A_{i,k}^{(U)}$, $\xi_{i,j}^{(L)}$, and $\theta_{i,k}^{(U)}$. Then, we use the Lagrangian multiplier method to solve the problem and obtain the globally optimal power and spectrum allocation. Hence, we minimize the total power consumption and improve the SE and EE of the URLLC system. The constructed Lagrangian function can be expressed 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 the Lagrangian multipliers.

Based on the KKT conditions, we can derive the globally optimal solutions of the spectrum and power allocation for the URLLC device i on licensed and unlicensed channels.

$$p_{i,j}^{(L)} = \xi_{i,j}^{(L)} W^{(L)} \left(\frac{\lambda_i}{\psi_i} - \frac{N_0}{h_{i,j}^{(L)}}\right)^{+}, \tag{11}$$

$$\xi_{i,j}^{(L)} = \frac{\lambda_i R_{i,j}^{(L)} - \psi_i p_{i,j}^{(L)}}{\alpha_j}, \tag{12}$$

$$p_{i,k}^{(U)} = W^{(U)} \left(\frac{\lambda_i}{\beta_k + \psi_i} - \frac{N_0}{h_{i,k}^{(U)}}\right)^{+}, \tag{13}$$

$$\theta_{i,k}^{(U)} = \frac{\lambda_i R_{i,k}^{(U)}}{\mu_k - \psi_i p_s^{(U)} - p_s^{(U)} + (\beta_k + \psi_i) A_{i,k}^{(U)}}, \tag{14}$$

where $(a)^+$ represents $\max(a, 0)$, α_j and μ_k are the Lagrangian multipliers of the constraints (9b) and (9c) on licensed and unlicensed spectrum restrictions respectively, β_k and ψ_i are the Lagrangian multipliers of the unlicensed band power limitation and total power limitation of the constraints (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 injection algorithm. It is clear that $p_{i,j}^{(L)}$ is related to $\xi_{i,j}^{(L)}$. Defined as $A_{i,k}^{(U)} = \theta_{i,k}^{(U)} \cdot p_{i,k}^{(U)}$, according to Eqs. (13) and (14), $p_{i,k}^{(U)}$ is also related to $\theta_{i,k}^{(U)}$.

3.2 Optimal Algorithm Development

Based on the above analysis, the detail of the algorithm steps to solve the optimization problem (9) can be summarized as in Algorithm 1. Firstly, according to equation (3), we can estimate the WiFi traffic load by the number of WiFi users and calculate the unlicensed time fraction for URLLC. Next, according to Eqs. (11), (12), (13), and (14), the Lagrangian multiplier method is adopted to obtain the globally optimal solutions of the optimization problem (9). Thus, we can acquire the optimal power and spectrum allocation for URLLC devices on licensed and unlicensed spectrums.

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 (11) and (12).
else if $0 < 1 - d_k^{(U)} < 1$ then
    The URLLC system simultaneously accesses licensed and unlicensed channels.
    According to (11), (12), (13), and (14), use the Lagrangian multiplier method to obtain 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 obtains the optimal solutions of $p_{i,k}^{(U)}$ and $\theta_{i,k}^{(U)}$ according to (13) and (14).
end if
return the globally optimal solution $P = \{p_{i,j}^{(L)}, \xi_{i,j}^{(L)}, p_{i,k}^{(U)}, \theta_{i,k}^{(U)}\}, \forall i, j, k$.
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4 Simulation Results

In this section, we provide numerical simulation results to demonstrate the effectiveness of the proposed URLLC power and spectrum allocation scheme for joint licensed and unlicensed bands. We first evaluate the performance of the URLLC system. Next, we analyze the impact of the available unlicensed spectrum resources.

In the simulation scenario, we consider a URLLC network with a BS. There are I URLLC devices randomly distribute within 50 m coverage of BS, and the arrival of data packets for all URLLC devices obeys a Poisson distribution. The mini-slot frame structure is adopted with the subcarrier of 30 kHz and 2 symbols. At the same time, we estimate the WiFi traffic load to calculate the unlicensed time fraction based on the number of WiFi users accessing the unlicensed bands. In addition, the licensed and unlicensed bandwidths are both 20 MHz. The licensed and unlicensed channels are Rayleigh fading channels. Other main simulation parameters are shown 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, N_0	−95 dBm (over 20 MHz BW)
Bandwidth on licensed and unlicensed, $W^{(L)}$, $W^{(U)}$	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

4.1 Performance Evaluation of the URLLC System

Figure 2 demonstrates the achievable SE of the URLLC system with different available time fractions on each unlicensed channel, $1 - d_k^{(U)}$, and data block length, with $L = 50,\ 200,\ 500$, and 800. As $1 - d_k^{(U)}$ increases, the SE of the system improves as well. Therefore, the more opportunities the system has to use the unlicensed spectrum resources, the higher SE the system can achieve.

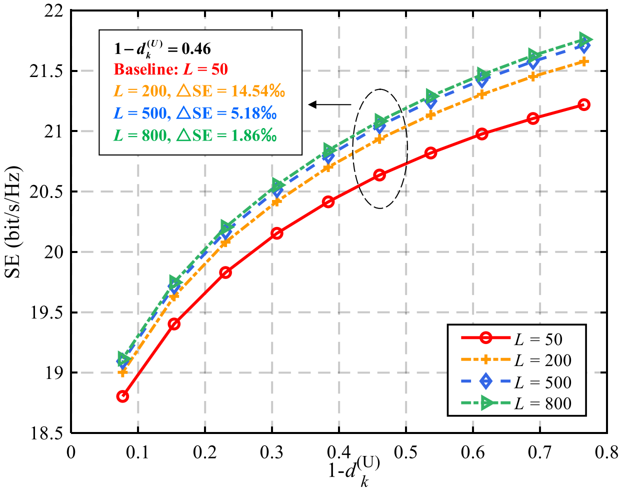


Fig. 2. The SE with different data block lengths and unlicensed time fractions.

Besides, as L increases, the proportion of control signaling overheads reduces and the effective data information increases, which would improve the SE. However, when L increases to 500, the SE improves only a little if continuing to increase the block length. We define a spectrum efficiency 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, $L = D_t W$ [15]. If continuing to increase L, it will bring more transmission delay or require more bandwidth. Thus, we compromise the transmission delay, channel bandwidth, and data rate of the URLLC system. It can be seen that $L = 500$ is the optimal block length in this simulation. In the subsequent simulations, L is selected to be 500 for other simulation analyses of optimal power and spectrum allocation.

Figure 3 depicts the total power consumption with different available time fractions and required minimum data rates, $r = 25$, 30, 35, and 40 Mbps. The increase on $1 - d_k^{(U)}$ implies that the available unlicensed spectrum resources for the URLLC devices increase. Therefore, the power consumption for listening to unlicensed channels to estimate the WiFi traffic loads decreases. In addition, Algorithm 1 optimizes the power and spectrum allocation, further reducing power consumption. However, as r increases, more transmission power is required to meet the rise on the data rate requirements.

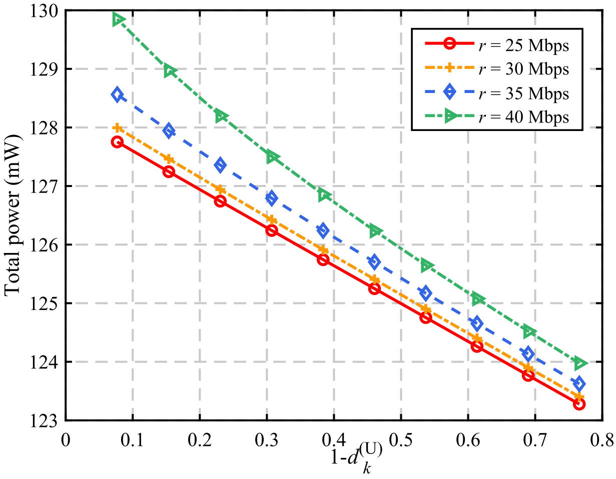
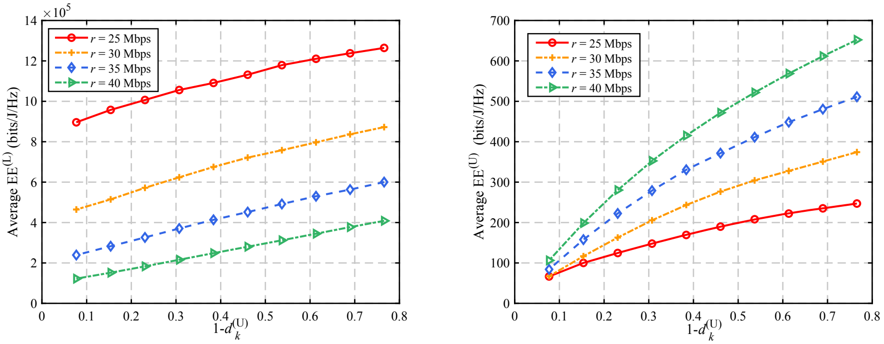


Fig. 3. The total power consumption with different unlicensed time fractions and minimum data rates.

4.2 Impact of the Available Unlicensed Spectrum Resource

Figure 4(a) shows the effect of Algorithm 1 on the EE achieved on licensed channels. When the available unlicensed spectrum resources increase, 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 spectrum more efficiently by Algorithm 1 to improve the EE on licensed channels. On the contrary, as r increases, the power consumption increases to satisfy the high transmission rate requirements, and the average EE decreases.



(a) The average EE on licensed band. (b) The average EE on unlicensed band.

Fig. 4. The average EE with different unlicensed time fractions and minimum data rates.

Figure 4(b) presents the impact of Algorithm 1 on the EE achieved on unlicensed channels. As the available unlicensed spectrum resources are close to 0, the EE achieved on unlicensed channels with different data rate requirements tends to 0. The EE improves with the increase of unlicensed spectrum resources. Different from the EE achieved on licensed channels, the EE increases when the data rate requirements increase. It is because the available unlicensed spectrum resources increase as the increase on 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 the unlicensed spectrum is generally lower than that of the licensed spectrum, as demonstrated in Fig. 4(a) and (b). That is because that the power consumption on unlicensed channels includes not only the transmission power, but also the sensing power. Thus, the power consumption on unlicensed channels is greater than that on licensed channels. In consequence, the average EE on unlicensed channels is relatively lower than that on licensed channels.

5 Conclusion

In this paper, we propose an optimal power and spectrum allocation scheme for the URLLC system. In order to reduce the power consumption, the unlicensed spectrum is exploited to serve the URLLC devices, and the DCM mechanism is adopted to ensure fair coexistence with the WiFi network. Moreover, we combine the user grouping scheme and mini-slot frame structure to make the URLLC system satisfy the low latency requirement. The finite block length regime is also employed to trade off the transmission data rate, finite block length, and transmission error probability. Then, we establish a power minimization model which meets the requirements of low latency and high reliability, and apply the Lagrangian multiplier method to derive the globally optimal expressions. Finally, simulation results illustrate that the joint use of licensed and unlicensed spectrums is beneficial to save energy, and the proposed scheme can effectively improve the SE and EE for the URLLC system.

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