Virtual resource mapping in inter-cell interference-constrained ultra-dense networks

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Abstract
Ultra-dense networking is considered an effective solution to achieve high capacity in 5G networks. However, the densely distributed base stations (BSs) in ultra-dense networks (UDNs) make the inter-cell interference much more serious than that in traditional cellular networks. Therefore, it is important to mitigate inter-cell interference in the UDNs to improve network performance. To tackle this problem, we propose a novel virtual resource mapping algorithm that includes a resource reservation (RR) algorithm and a real-time resource embedding (RE) algorithm. Specifically, according to the number of services predicted by a dynamic service model, the RR algorithm is proposed to determine the sets of multiplexing BSs in the next time cycle and reserve channel resource required by each BS. Then, to further reduce inter-cell interference, the real-time RE algorithm is proposed to allocate the channel resource in real time. Finally, simulation results show that the proposed algorithm has better performance in terms of signal-to-interference-plus-noise ratio and acceptance ratio, compared to the existing algorithms, such as the frequency reuse channel allocation algorithm and inter-cell interference coordination algorithm.

1 | INTRODUCTION

5G wireless networks are expected to provide ultra-low latency experience, ultra-high connection density and mobility. Faced with diversified services, the researchers classify 5G service scenarios into three types, that is, massive machine-type communication, ultra-reliable and low-latency communication, and enhanced mobile broadband (eMBB). In the eMBB scenarios such as gyms and supermarkets, researchers focus on high-capacity requirements and propose some techniques to meet the requirements in their studies [1–5]. Among these techniques, ultra-dense networking is considered a useful solution for enhancing wireless network capacities by deploying a great number of small base stations (BSs) [2], for example, 1000 times improvement of data traffic and 10 to 100 times improvement of user rate in the future 5G networks [3]. However, the inter-cell interference in ultra-dense networks (UDNs) becomes more serious, compared to traditional cellular networks, and also limits the performance gain. Therefore, how to reduce the inter-cell interference is an urgent problem to be solved.

The 5G network architecture encompasses different techniques, such as software-defined networking and network function virtualisation (NFV), and these techniques allow for the separation of the control plane from the data plane [4], the disaggregation of network functionalities, the slicing and virtualisation of network resources. This work is based on the NFV technique and reasonably configure node and link resources in the entire network through resource mapping algorithms [6] to reduce interference and improve network performance. Our contributions are listed below.
1. We consider a UDN scenario with a great number of BSs and ultra-dense service requests of users. A virtual resource mapping algorithm including a resource reservation (RR) algorithm and a real-time resource embedding (RE) algorithm is proposed to mitigate the intra- and inter-cell interference.

2. According to the number of services predicted by a dynamic service model, the RR algorithm is proposed to determine the sets of multiplexing BSs in the next time cycle and reserve channel resource required by each BS.

3. In addition, to further reduce inter-cell interference, the real-time RE algorithm is proposed to allocate the channel resource in real time and stagger the time that the multiplexing BSs use as the same channels by sequencing channel allocation.

4. Finally, simulation results are presented to validate the performance of the proposed algorithm by comparing the proposed algorithm with the baseline algorithms, such as the frequency reuse channel allocation (FRCA) algorithm [30] and inter-cell interference coordination (ICIC) algorithm [31].

2 | RELATED WORKS

NFV technique is used to make multiple tenants share a common physical network [7] and is the most commonly employed method of resource mapping. Resource mapping algorithms based on network virtualisation are studied in both wired and wireless scenarios.

In the wired scenarios, Yu et al. [8] proposed a path splitting algorithm, which used multiple underlying network links to allocate the virtual link bandwidth. Chowdhury et al. [9] established a mapping model based on the topology and graph theories to maximise network capacity. In [10], Chowdhury et al. also established a mapping model based on the mixed-integer programming and found the optimal solution for maximising network capacity through relaxing integer constraints.

Unlike the wired scenarios, a simple and fixed resource allocation method may not satisfy user requirements in the wireless scenarios due to the dynamics of wireless channels. Zhu et al. [11] comprehensively considered the interests of operators and user requirements and formulated the resource allocation problem as a game. Hsu et al. [12] reformulated the channel allocation problem as a two-dimensional rectangular strip packing problem and the bottom-left algorithm was used to improve the channel utilisation. Yang et al. [13] proposed a Karnaugh map-like virtual resource mapping algorithm, which used the Karnaugh map to calculate the remaining resources and adopted the greedy algorithm to optimise resources allocation.

To mitigate the inter-cell interference, several existing works [14–18] studied different resource allocation methods. Lopez-Perez et al. [14] proposed autonomous and coordinated resource allocation algorithms combined with the self-organisation rule and the resource allocation limits. Gueguen et al. [15] proposed a dynamic ICIC method to deal with non-homogeneous distribution of users. Wang et al. [16] proposed an adaptive resource allocation method, which optimised the resource allocation scheme according to the interference distribution and service load. Gang et al. [17] proposed a proportional fair scheduling based on the radio resource allocation method for the multi-cell orthogonal frequency division multiple access system. Karthik et al. [18] proposed a greedy power allocation method, which achieved significant performance improvement for cell-edge users and desirable performance for cell-centre users. Unlike these prior works that only considered real-time resource allocation, we perform the RR before the resource allocation process, which reserves the channel resource for each BS according to the predicted maximum number of the existing services.

Our research mainly focuses on the channel resource allocation in 5G UDNs based on the wireless virtual mapping. The remaining part of this paper is organised as follows: Section 3 describes the system model, service model and the prediction model of dynamic services. The considered problem is formulated in Section 4, and the virtual resource allocation algorithm is proposed in Section 5. Furthermore, simulation results are presented in Section 6, and finally conclusions are drawn in Section 7.

3 | SYSTEM MODEL

3.1 | Network model

This paper considers a UDN that includes a large number of BSs with ultra-dense service requests of users as shown in Figure 1. The spectrum resource is virtualised into a virtual pool and the BSs allocate channels of the same bandwidth $\omega_0$ to different services. Thus, the number of orthogonal channels is $M = W / \omega_0$, where $W$ is the total bandwidth.

We denote the sets of the BSs and the channels as $N = \{1, 2, ..., N\}$ and $M = \{1, 2, ..., M\}$, respectively. The channel reservation matrix of the entire network is denoted as $D = \{D_1, D_2, ..., D_N\}$, where $D_n$ denotes the channel reservation matrix of BS $n \in N$ and is given as

$$D_n = \begin{bmatrix} d^{1}_{n,1} & d^{1}_{n,2} & d^{1}_{n,3} & d^{1}_{n,4} & \cdots & d^{1}_{n,M} \\ d^{2}_{n,1} & d^{2}_{n,2} & d^{2}_{n,3} & d^{2}_{n,4} & \cdots & d^{2}_{n,M} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ d^{x_n}_{n,1} & d^{x_n}_{n,2} & d^{x_n}_{n,3} & d^{x_n}_{n,4} & \cdots & d^{x_n}_{n,M} \end{bmatrix}$$

(1)

where $x_n^k$ stands for the number of channels that are allocated to BS $n$ under a certain probability (presented in Section 3.3) and $d^{k}_{n,m} \in \{0, 1\}$. If service $k$ occupies channel $m$ of BS $n$, then $d^{k}_{n,m} = 1$; otherwise $d^{k}_{n,m} = 0$.

The downlink scenario [19, 20] is considered in this paper with the following reasonable assumptions:

1. The radio coverage of a BS in the UDN is small; thus, the distance between a BS and a user served by a neighbouring BS is assumed to be the distance between the two BSs. The distance between the user and its communication BS is assumed as the communication radius of the BS.
2. The channels are allocated to the services in each time cycle. A channel is allocated to at most one service in the same cell to prevent the intra-cell interference, and each service can occupy at most one channel within a time cycle, that is,

\[ \sum_{k=1}^{x_n} d_{k,m} \leq 1, \quad \forall m \in M, \forall n \in N, \quad (2) \]

\[ \sum_{m=1}^{M} d_{k,m} \leq 1, \quad \forall k \in \{1, 2, ..., x_n\}, \forall n \in N, \quad (3) \]

3. For any BS, the number of services within a time cycle does not exceed the number of channels in order to prevent intra-cell interference.
4. The pilot-based channel estimation algorithms are adopted \([21, 22]\) and perfect channel state information (CSI) is available.

### 3.2 Service model

Similar to \([23–25]\), we model the arrival of services of each BS as a Poisson process and define \(\lambda_n\) as the arrival rate. In each time cycle, the probability density function of \(r\) service arrivals is given as

\[ P_r^\text{arr}(t) = \frac{(\lambda_n t)^r}{r!} e^{-\lambda_n t}, \quad r = 0, 1, 2, 3, ... \quad (4) \]

The service time is assumed to follow the exponential distribution \([23–25]\), and the probability density function is given as

\[ f(x) = \begin{cases} \lambda_c e^{-\lambda_c x} & x > 0 \\ 0 & x \leq 0 \end{cases} \quad (5) \]

where \(\lambda_c = \frac{1}{\mu_c}\) and \(\mu_c\) is the average service time.

Assume that the number of remaining services of BS \(n\) in the current time cycle is \(K_n\). Then, based on Equation (5), the probability distribution of \(q\) finished services in the next time cycle is denoted as

\[ P_q^\text{fin}(K_n) = C_q^{K_n} \Theta(t \leq \tau)^q \Theta(t > \tau)^{K_n-q} \]

\[ = C_q^{K_n} \left(1 - e^{-\lambda_n \tau}\right)^q e^{-\lambda_n \tau}, \quad (\tau > 0) \quad (6) \]

where \(q = 0, 1, ..., K_n, C_q^{K_n} = \frac{K_n!}{q!(K_n-q)!}\), and

\[ (t \leq \tau) = \int_0^\tau \lambda_c e^{-\lambda_c x} dx = \left[1 - e^{-\lambda_c \tau}\right]. \quad (7) \]

### 3.3 Prediction model of dynamic services

Note that the number of services in each time cycle is varying and we denote the maximum number of the existing services in the time cycle \(t\) as \(\varphi_t\). According to the arrival model (4) of services, the maximum number \(\varphi_{t+1}\) of the existing services in the next time cycle can be predicted. We assume that the remaining services in the previous time cycle have priority over those in the current time cycle to be allocated channel resource by the BSs. Besides, when a service is finished, the released channel can be allocated to the subsequent services.

For the considered scenario, two boundaries of the maximum number \(\varphi_t\) of the services are given as follows:

1. Upper boundary: In the current time cycle, the remaining services in the previous time cycle are finished after new services arrive. Thus, the maximum number of existing services is the sum of the remaining services in the previous time cycle and the arriving services in the current time cycle.
2. Lower boundary: In the current time cycle, after all remaining services in the previous time cycle are finished, new services start to arrive. Hence, the minimum number of existing services is the number of remaining services in the previous time cycle.

Therefore, the number of existing services is between the upper and lower boundaries. See Appendix A for more details.

When predicting the number of services in the next time cycle, we need to consider not only the numbers of arriving services and the finished services but also the combinations of the service arrival and completion. Given that the number of arriving services is \( r \) and the number of finished services is \( q \), the corresponding occurrence probability is denoted as \( P_r^\text{arr}(\tau)P_q^\text{fin}(K_n) \). Considering the events of service arrival and completion, the occurrence probability of the situation where the maximum number of existing services is \( K_n + S \) in the next time cycle is given as

\[
P(x_n = K_n + S|K_n) = \sum_{r=0}^{\infty} \sum_{q=0}^{g} \frac{G(q;K_n+S)}{C_{q+g}^r} P_r^\text{arr}(\tau) P_q^\text{fin}(K_n) \tag{8}
\]

where \( G(q;K_n+S) \) represents the occurrence times of the situation where the maximum number of existing services is \( K_n + S \), the number of finished services is \( q \) in the next time cycle, and \( C_{q+g}^r \) represents the event combinations of \( r \) arriving services and \( q \) finished services in the next time cycle. See Appendix B for more details.

The confidence possibility is derived as

\[
P(x_n \leq K_n + S|K_n) \geq 1 - \xi, \tag{9}
\]

where \( 1 - \xi \) is the confidence level. The inequality (9) indicates that the occurrence possibility in which the maximum number of existing services of BS \( n \) in the next time cycle will not exceed \( K_n + S \) is not less than \( 1 - \xi \). The minimum value that satisfies the inequality (9) is denoted as \( x_n^* \) (\( x_n^* \in N^+ \)).

Based on the inequality (9), the possible number of services with a certain confidence level in the next time cycle can be predicted. Then, according to the prediction results, we can know in advance how the channel resource will be allocated to the BSs in the next time cycle.

4 | PROBLEM FORMULATION

4.1 | Channel model

The path loss model is given as [26, 27]

\[
\text{PL}(l) = \text{Loss}(l) + 10\log(l/h_0) + \varepsilon \tag{10}
\]

where \( l \) is the propagation distance, \( h_0 \) is the reference distance, \( \varepsilon \) is the path-loss exponent, \( \varepsilon \) is the loss coefficient, and

\[
\text{Loss}(l) = 32.4 + 20\log(l) + 20\log(f),
\]

in which \( f \) is the carrier frequency.

In this work, the interference between the BSs and users, as well as that between the BSs, is considered. The interference power received by the user who requests service \( k \) in BS \( n \) is computed as

\[
I_{n,k} = \sum_{n'=1}^{N} \sum_{k'=1}^{M} d_{n,m}^{k} d_{n,m}^{k} P_{BS} b(l_{n,n'}) \tag{11}
\]

where \( P_{BS} \) is the transmit power of the BSs, \( l_{n,n'} \) denotes the distance between BSs \( n \) and \( n' \), and \( b(l_{n,n'}) = 10^{PL(l_{n,n'})/10} \). Note that only the services occupying the same channel in different BSs can cause the inter-cell interference.

The signal-to-interference-plus-noise ratio (SINR) of the user who requests service \( k \) in BS \( n \) is denoted as

\[
\text{SINR}_{n,k} = \frac{P_{BS} b(l_{n,k})}{I_{n,k} + \sigma^2} \tag{12}
\]

where \( \sigma^2 \) is the noise power.

4.2 | Problem formulation

In this work, we aim to maximise the sum of all users’ SINRs in the considered UDN with the quality of service (QoS) constraints, which is formulated as

\[
(p1) \quad \text{maximise } \sum_{n=1}^{N} \sum_{k=1}^{N} \text{SINR}_{n,k} \quad \text{s.t.} \quad C1: \sum_{m=1}^{M} d_{n,m}^{k} \leq 1, \quad \forall n, m,
\]

\[
C2: \sum_{k=1}^{N} d_{n,m}^{k} = 1, \quad \forall n, k,
\]

\[
C3: x_n^* \leq M, \quad \forall n,
\]

\[
C4: d_{n,m}^{k} \in \{0, 1\}, \quad \forall n, m, k,
\]

\[
C5: \text{SINR}_{n,k} \geq \text{SINR}_{n,b}, \quad \forall n, k
\]

\[
C6: n \in N, \quad m \in M, \quad k \in \{1, 2, ..., x_n^*\} \tag{13}
\]

where \( C3 \) represents the number constraint of services and \( C5 \) represents the QoS constraints.

According to the inequality (9), we find that the predicted maximum number \( x_n^* \) of the existing services is larger if the confidence coefficient \( 1 - \xi \) is larger. As a consequence, the calculated inter-cell interference will increase and even the constraint \( C5 \) is not satisfied. If the confidence level \( 1 - \xi \) is small, the predicted number of services will be inaccurate, and idle channel resource will not be reserved for BSs. Then, the effectiveness of the RR is degraded. Based on the above analysis, we take into
account the influence of $\xi$ and reformulate the SINR maximisation problem (p1) as

\[(p2): \text{maximise} \max_{\forall d_{n,m}} \frac{1}{\xi} \left( \sum_{a=1}^{N} \sum_{k=1}^{x_{a}^{*}} \text{SINR}_{a,k} + w \left( 1 - \xi \right) \right) \]

s.t. $C1 - C5$

\[C7: x_{a}^{*} = \arg\min_{\mathcal{B}_{n} \leq 1 + k, |k| \geq 1 - \xi} \{ x_{a} \}, \ \forall n, \]

\[C8: w > 0, \ 1 > \xi > 0, \ n \in \mathcal{N}, \]

\[k \in \{1,2,...,x_{a}^{*}\}, \ m \in \mathcal{M}, \] \hfill (14)

where $w$ is a weight coefficient. To prevent $1 - \xi$ from being too small in the solution, the value of $w$ should be a large value. In addition, when there are feasible solutions to the problem (p2), $1 - \xi$ should be as large as possible to improve the confidence level.

Since the useful signal power $P_{bs}b(l_{a,k})$ received by each user and the noise power are both constants, the SINR maximisation problem (p2) can be equivalently formulated as

\[(p2.1): \text{minimise} \max_{\forall d_{n,m}} \frac{1}{\xi} \left( \sum_{a=1}^{N} \sum_{k=1}^{x_{a}^{*}} \text{I}_{a,k} + w \cdot \xi \right) \]

s.t. $C5.1: I_{n,k} \leq I_{th}, \ \forall n, k,$

$C1 - C4, C7, C8$ \hfill (15)

where $I_{th}$ represents the inference threshold.

## 5 Proposed Algorithm

The considered channel allocation problem in this paper is an integer programming and there are some common algorithms for this problem, such as the exhaustive method and the implicit enumeration method [28, 29]. However, the computational complexity of the methods mentioned above is too high and the caused delay is usually unacceptable. To solve the channel allocation problems, we propose an RR algorithm based on the implicit enumeration method. In the proposed RR algorithm, the multiplexing BS sets are determined and the channel resource is reserved for each BS based on the prediction of the maximum number $\{x_{a}^{*}, n \in \mathcal{N}\}$ of the existing services. Specifically, according to the QoS constraints, we set the distance range between multiplexing BSs and determine the multiplexing BS sets. Then, by traversing all BSs that meet the distance limit, we can get different combinations of multiplexing BS sets (MSs) and select a combination of multiplexing BS sets with the largest $L_{MS}$. Finally, according to the predicted number of services and the selected MS, we reserve channel resource for each BS by the implicit enumeration method (MSs and $L_{MS}$ are defined in Section 5.1).

Note that the channels are reserved for the BSs in the phase of channel reservation, and the channels are not allocated the services before the phase of RE. Therefore, the channel reservation matrix $D$ can be simplified as

\[
D = \begin{bmatrix}
    d_{1,1} & d_{1,2} & d_{1,3} & \cdots & d_{1,M} \\
    d_{2,1} & d_{2,2} & d_{2,3} & \cdots & d_{2,M} \\
    \vdots & \vdots & \vdots & \ddots & \vdots \\
    d_{N,1} & d_{N,2} & d_{N,3} & \cdots & d_{N,M}
\end{bmatrix}
\] \hfill (16)

where $d_{n,m} = 1$ if channel $m$ is allocated to BS $n$, otherwise $d_{n,m} = 0$. Then, the interference received by the user occupying channel $m$ in BS $n$ is given as

\[
I_{n,m} = \sum_{a=1, a \neq n}^{N} d_{n,m} d_{a,m} P_{bs} b(l_{a,m}) \] \hfill (17)

The improved optimisation model is rewritten as

\[(p3): \text{minimise} \max_{\forall d_{n,m}} \frac{1}{\xi} \left( \sum_{a=1}^{N} \sum_{m=1}^{M} I_{n,m} + w \cdot \xi \right) \]

s.t. $C2.1: \sum_{m=1}^{M} d_{n,m} = x_{a}^{*}, \ \forall n,$

$C4.1: d_{n,m} \in \{0,1\}, \ \forall n, \forall m,$

$C5.1: I_{n,m} \leq I_{th}, \ \forall n, \forall m,$

$C3, C7, C8,$ \hfill (18)

where $C2.1$ shows that the number of channels allocated to BS $n$ is equal to the predicted maximum number $x_{a}^{*}$ of the existing services.

It is still hard to find the optimal solution to problem (p3), especially when $M$ is large. To resolve this challenge, we first find the BSs that can be allocated the same channel resource, and we refer to such BSs as the multiplexing BSs. After the multiplexing BSs are determined, the channel allocation is performed to obtain the solutions.

The inter-cell interference matrix is represented as

\[
I_{LL} = \begin{bmatrix}
    \infty & b(l_{1,2}) & b(l_{1,3}) & \cdots & b(l_{1,N}) \\
    b(l_{2,1}) & \infty & b(l_{2,3}) & \cdots & b(l_{2,N}) \\
    \vdots & \vdots & \vdots & \ddots & \vdots \\
    b(l_{N,1}) & b(l_{N,2}) & b(l_{N,3}) & \cdots & \infty
\end{bmatrix} P_{BS}
\] \hfill (19)
where $L$ denotes the $N \times N$ distance matrix between the BSs. Note that $\infty$ suggests that different services in the same BS need to use different channels. Otherwise, the communication may fail due to serious intra-cell interference. Hence, the multiplexing BSs can be selected based on the distance limit, and the interference of the entire network can be mitigated.

### 5.1 Algorithm

The predicted maximum number $x_i^m$ of the existing services of all the BSs are collected into a set $X^* = \{ x_1^m, x_2^m, ..., x_N^m \}$. The number of channels is much smaller than the total number of the services of all the BSs, that is, $M < \sum_{i=1}^{N} x_i^m$; thus, the BSs need to perform channel multiplexing. The average number of services per BS is $\bar{X} = \frac{\sum_{i=1}^{N} x_i^m}{N}$, and the number of multiplexing BSs is $N_f = N \cdot \bar{X} / M$. The $N$ BSs are divided into $N_f$ sets, and the BSs in different sets do not interfere with each other. In order to mitigate the inter-cell interference, we assume that the distance between the two multiplexing BS must be greater than or equal to the minimum distance $l_{\text{min}}$, which is chosen according to the interference threshold $I_{\text{th}}$. Furthermore, in order to avoid too many BSs being assigned into the same set and reduce the dimension of the solution space, the maximum distance between the multiplexing BSs is also set as $l_{\text{max}}$. That is to say, only the BSs with distance belonging to $[l_{\text{min}}, l_{\text{max}}]$ can be chosen as the multiplexing BSs. The BSs in a multiplexing set are allocated the same channel resource. We denote $i$-th multiplexing BS set by $MS_i, i \in \{ 1, 2, 3, ..., N_f \}$ and define $MS = \{ MS_1, MS_2, ... , MS_{N_f} \}$. The distance $L_{MS}$ represents the sum of the distances between the BSs in $MS_i$, and the total distance is defined as $L_{MS} = \sum_{i=1}^{N_f} L_{MS_i}$. For a BS set $BS$, $L_{BS_{\text{sum}}}$ means all distances between all BSs of $BS$ and the BS $n$.

### 5.2 Real-time RE algorithm

Based on the RR algorithm, we can find the channel reservation matrix and the multiplex BS sets to better guarantee user experience and mitigate inter-cell interference in the entire network. In actual channel allocation, we also consider the specific channel allocation sequence for each time cycle to improve the instantaneous SINR. Before the service is only executed after the channel is allocated, we can reduce the interference time from other BSs in the process of the service execution by sequencing the channel allocation so as to improve the instantaneous SINR. Since the channels that are used by the BSs of the different sets are orthogonal, we only need to consider real-time channel allocation in each multiplexing BS set separately. Applying this method to other multiplex BS sets can increase the instantaneous SINR of the entire network. To further improve the instantaneous SINR, the compound sequence distance is defined as

$$
L_s(n_1, n_2, n_3) = f \left( \frac{L_{n_1, n_2}^{m}}{L_{n_1, n_2}^{m} + L_{n_1, n_3}^{m}} \right) + \frac{L_{n_1, n_2}^{m}}{L_{n_1, n_3}^{m} + L_{n_1, n_2}^{m}} \tag{20}
$$

where $l_{n_1, n_2}^{m}$ represents the sequence distance, which represents the difference between the allocation sequences of the channel $m$ in the BS $n_1$ and in the BS $n_2$, $l_{n_1, n_2}^{m}$ represents the inter-cell distance about the BS $n_1$ and the BS $n_2$. For example, if channel $m$ is ranked first in BS $n_1$ and ranked fourth in BS $n_2$, the sequence distance $l_{n_1, n_2}^{m} = 3$. Equation (20) is an increasing function of $l_{n_1, n_2}^{m}$ and $l_{n_1, n_2}^{m}$. When the inter-cell distance is small, the sequence distance has a great effect on this function. However, the inter-cell distance is large, the sequence distance has little effect on this function. The total distance of a channel is the sum of the compound sequence distances of this channel in the multiplex BSs. The instantaneous SINR increases with the increasing of the total distance.

In this study, the greedy algorithm will be used to sequence the channel allocation. In all BS sets of channel multiplexing, the channels of the two closest BSs are sequenced by the greedy algorithm so that the compound sequence distance is the largest. And then, the BS closest to the two BSs is searched, and the channels of the BSs are sequenced by the greedy algorithm so that the compound sequence distance is the largest. Finally, the channels of all BSs in the entire network are sequenced.
Algorithm 2 Real-time RE algorithm

Input: \( D \) and \( MS \).
Output: Channel allocation sequence for each BS.

1. if \( i \leq NZ \):
2. if \( x = \max\{x^* | n \in MS_i\} \):
3. Schedule the channel allocation sequence of BS \( n \), \( MS_i = MS_i - \{n\} \), and \( AS_i = \{n\} \).
4. end if
5. if \( l_{AS_i,n'} = \min\{l_{AS_i,n'} | n' \in MS_i\} \):
6. Schedule the channel allocation sequence of BS \( n' \) by the greedy algorithm, \( MS_i = MS_i - \{n'\} \), and \( AS_i = AS_i + \{n'\} \).
7. end if
8. Repeat 5–7 until the set \( MS_i \) is empty.
9. \( i = i + 1 \).
10. end if

Table 1 Simulation parameters

| Parameter                  | Value       |
|----------------------------|-------------|
| Length of time cycle       | 60 s        |
| Transmit power of each BS  | 30 dBm      |
| Channel bandwidth \( \bar{\alpha}_s \) | 1.5 kHz     |
| Number of channels \( M \) | 100         |
| The number of remaining services \( K_n \) | (10,20) |
| Service arrival rate \( \lambda_s \) | (0.05,0.2) |
| Average service time \( \bar{u}_s \) | 60 s        |
| Confidence coefficient \( \bar{\xi} \) | (0.1,0.6)   |
| Noise power \( \sigma^2 \) | 5 \times 10^3 \text{Hz} |
| User experience guarantee \( \text{SINR}_{th} \) | 9 dB         |
| Weight coefficient \( w \) | 10^5        |
| The maximum distance \( l_{max} \) | 2\( l_{max} \) |

6.1 SIMULATION RESULTS

In this section, we present the simulation results to evaluate our proposed algorithm in an area of size 200 × 200 m. To achieve seamless coverage, 25 BSs are evenly deployed in the area, and the average communication radius of the cells is set as 20 m. More system-related simulation parameters are listed in Table 1.

For comparison, we introduce four baseline algorithms, including FRCA algorithm [30], which fixes the channel usage of each BS; ICIC algorithm [31], which uses high transmission power for cell-edge users and low transmission power for cell-centre users; the RR algorithm without the real-time RE algorithm; and the FRCA+RE algorithm, which first executes the fixed channel allocation and then performs the real-time RE.

In Figure 2, we find that the predicted number of services decreases with the increase of the length of each time cycle. When \( \bar{\xi} = 0.1 \), the predicted number of services is much larger than the actual value in most cases, but when \( \bar{\xi} = 0.3 \), the predicted number of services exceeds the actual value only in the cases with a large time cycle. We also find that when \( \bar{\xi} = 0.2 \) and the length of time cycle is 60 s, the predicted number of services is slightly higher than the actual value. Based on the above observations, we choose 60 s as the length of time cycle in our simulations.

Figure 3 shows the confidence coefficient \( \bar{\xi} \) with respect to the number \( M \) of orthogonal channels with different values of weight coefficient \( w \). According to the results shown in Figure 3, we can select \( w \) as a large value that can prevent \( \bar{\xi} \) from being too large to improve the confidence level. In addition, when \( w \) is too large, the small value \( \bar{\xi} \) will cause the predicted number of services to be much higher than the actual value. So we select \( w = 10^5 \) in our research.

Figures 4(a) and (b) compare the real-time SINR values of the proposed algorithm and the baseline algorithms with \( M = 100 \) and \( M = 200 \), respectively. Among these algorithms, the performance of the proposed algorithm is the best and that of the RR algorithm is slightly worse. The achieved SINR values of the FRCA and ICIC algorithms are close to each other.
The simulation results confirm that the RR algorithm can effectively reduce inter-cell interference by limiting the distance of the multiplexing BS in UDNs. The achieved SINR value of the FRCA+RE algorithm is higher than that of the FRCA algorithm, which shows that the real-time RE algorithm can improve the real-time SINR. Besides, the effect of the real-time RE algorithm will be better as $M$ increases.

Figures 5(a) and (b) show the real-time acceptance ratio of different algorithms with $M = 100$ and $M = 200$, respectively. The curve of the RR algorithm is very close to the proposed algorithm because they use the same channel allocation algorithm. Similarly, the curves of the FRCA and FRCA+RE algorithms are close to each other. When the number of channels was small, the real-time acceptance ratio of the proposed algorithm is the largest, whereas that of the FRCA algorithm is the smallest. This is because the ICIC algorithm increases the system capacity, and the ICIC algorithm has a greater real-time acceptance ratio than the FRCA algorithm. However, the ICIC algorithm is not as well as the proposed algorithm for processing some services; the ICIC algorithm has a lower real-time acceptance ratio than the proposed algorithm.

Figures 6 and 7 depict that the average SINR and average acceptance ratio of several algorithms increase with the increase of channel number. The proposed algorithm is superior to other algorithms. According to the simulation results, the proposed algorithm outperforms ICIC and FRCA algorithms in terms of SINR and acceptance ratio in the hotspot scenarios. Moreover, when the number of services is over the capacity of the system, the proposed algorithm could also ensure the user experience and execute services as much as possible.

7 | CONCLUSION

In this paper, we mainly studied the mapping algorithm of wireless resource for 5G UDNs with dynamic services. Based on the characteristics of the service arrival and service time, a
probability model of dynamic services was established to predict the number of services. According to the predicted value, the RR algorithm and the real-time embedding algorithm were proposed to improve the SINR of the entire network with guaranteed QoS. Finally, the simulation results showed the effectiveness of the proposed algorithm. This work was done under the assumption that perfect CSI is available. However, in practical scenarios, only imperfect CSI is available due to estimation errors. Our future work is to extend the proposed algorithm into the scenarios with imperfect channel estimation.

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The current time cycle is finished services is given that the number of arriving services is $r$. The probability that the number of services is $K_r$ is
\[
\sum_{x=0}^{K_r} P_r(x) P_{\text{fin}}(x) P_{\text{arr}}(x).
\]

The probability that the number of services is $K_r$ is
\[
\sum_{x=0}^{K_r} P_r(x) P_{\text{fin}}(x) P_{\text{arr}}(x).
\]

The probability that the number of services is $K_r+1$ is
\[
\sum_{x=0}^{K_r+1} P_r(x) P_{\text{fin}}(x) P_{\text{arr}}(x).
\]

The probability that the number of services is $K_r+2$ is
\[
\sum_{x=0}^{K_r+2} P_r(x) P_{\text{fin}}(x) P_{\text{arr}}(x).
\]

The probability that the maximum number of existing services in the next time cycle (times)

\[
(0,0), \quad K_r (\text{once})
\]

\[
(0,1), \quad K_r+1 (\text{once,0})
\]

\[
(0,2), \quad K_r (\text{once,00})
\]

\[
(0,3), \quad K_r (\text{once,000})
\]

\[
\vdots
\]

\[
(1,0), \quad K_r+1 (\text{once,1})
\]

\[
(1,1), \quad K_r+1 (\text{once,10})
\]

\[
(1,2), \quad K_r+1 (\text{once,100})
\]

\[
(1,3), \quad K_r+1 (\text{once,1000})
\]

\[
\vdots
\]

\[
(2,0), \quad K_r+2 (\text{once,11})
\]

\[
(2,1), \quad K_r+2 (\text{once,110})
\]

\[
(2,2), \quad K_r+2 (\text{once,1100})
\]

\[
\vdots
\]

**APPENDIX**

**A. Maximum number of the existing services**

Given that the number of arriving services is $r$, the number of finished services is $q$, and the number of remaining services in the current time cycle is $K_r$. The maximum number of existing services in the next time cycle will be represented as (0 denotes a finished service, and 1 denotes an arriving service)

The probability that the number of services is $K_r$ is
\[
\sum_{x=0}^{K_r} P_r(x) P_{\text{fin}}(x) P_{\text{arr}}(x).
\]

The probability that the number of services is $K_r+1$ is
\[
\sum_{x=0}^{K_r+1} P_r(x) P_{\text{fin}}(x) P_{\text{arr}}(x).
\]

The probability that the number of services is $K_r+2$ is
\[
\sum_{x=0}^{K_r+2} P_r(x) P_{\text{fin}}(x) P_{\text{arr}}(x).
\]

**B. Derivation of $G(q, K_r + S)$**

The $G(q, K_r + S)$ depicts possible situations where the maximum number of existing services is $K_r + S$, and the number of finished services is $q$ in the next time cycle.

After analysis, we can get the following rules. where ‘time’ denotes the number of different situations. For example, when $r = 1, q = 2$, and the number of remaining services is $K_r$, we can get ‘2 times’, because there are two situations: ‘010’ and ‘001’. The numbers in the red region satisfy a law similar to Fibonacci.
The maximum number of existing services in the next time cycle

| r  | \( K_{n+1} \) | \( K_n \) |
|----|----------------|----------|
| 1  | \( K_{n+1} \) | \( K_n \) |
| 2  | \( K_{n+2} \) | \( K_{n+1} \) | \( K_n \) |
| 3  | \( K_{n+3} \) | \( K_{n+2} \) | \( K_{n+1} \) | \( K_n \) |
| 4  | \( K_{n+4} \) | \( K_{n+3} \) | \( K_{n+2} \) | \( K_{n+1} \) | \( K_n \) |

| q  | \( 0 \)     | \( 1 \)     | \( 2 \)     | \( 3 \)     | \( 4 \)     | \( 5 \)     | ... |
|----|--------------|--------------|--------------|--------------|--------------|--------------|-----|
| 0  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |
| 1  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |
| 2  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |
| 3  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |
| 4  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |
| 5  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |

The maximum number of existing services in the next time cycle

| r  | \( K_{n+1} \) | \( K_n \) |
|----|----------------|----------|
| 1  | \( K_{n+1} \) | \( K_n \) |
| 2  | \( K_{n+2} \) | \( K_{n+1} \) | \( K_n \) |
| 3  | \( K_{n+3} \) | \( K_{n+2} \) | \( K_{n+1} \) | \( K_n \) |
| 4  | \( K_{n+4} \) | \( K_{n+3} \) | \( K_{n+2} \) | \( K_{n+1} \) | \( K_n \) |

| q  | \( 0 \)     | \( 1 \)     | \( 2 \)     | \( 3 \)     | \( 4 \)     | \( 5 \)     | ... |
|----|--------------|--------------|--------------|--------------|--------------|--------------|-----|
| 0  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |
| 1  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |
| 2  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |
| 3  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |
| 4  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |
| 5  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |

The maximum number of existing services in the next time cycle

| r  | \( K_{n+1} \) | \( K_n \) |
|----|----------------|----------|
| 1  | \( K_{n+1} \) | \( K_n \) |
| 2  | \( K_{n+2} \) | \( K_{n+1} \) | \( K_n \) |
| 3  | \( K_{n+3} \) | \( K_{n+2} \) | \( K_{n+1} \) | \( K_n \) |
| 4  | \( K_{n+4} \) | \( K_{n+3} \) | \( K_{n+2} \) | \( K_{n+1} \) | \( K_n \) |

| q  | \( 0 \)     | \( 1 \)     | \( 2 \)     | \( 3 \)     | \( 4 \)     | \( 5 \)     | ... |
|----|--------------|--------------|--------------|--------------|--------------|--------------|-----|
| 0  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |
| 1  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |
| 2  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |
| 3  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |
| 4  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |
| 5  | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       | 1 time       |     |
We find the following conclusion:

| $r = j$ | $K_n + j$ | $K_n + j - 1$ | $K_n + j - 2$ | $K_n + j - 3$ | $K_n + j - 4$ | … |
|---------|-----------|---------------|---------------|---------------|---------------|---|
| $q = 0$ | 1         |               |               |               |               |   |
| $q = 1$ | 1         | $f_j(1)$      |               |               |               |   |
| $q = 2$ | 1         | $f_j(1) + 1$  |               |               |               |   |
| $q = 3$ | 1         | $f_j(1) + 2$  | $f_j(1) + f_j(2) + 1$ |               | $f_j(3)$   |   |
| $q = 4$ | 1         | $f_j(1) + 3$  | $2f_j(1) + f_j(2) + 3$ | $f_j(1) + f_j(2) + f_j(3) + 1$ |               | $f_j(4)$ |
| $q = 5$ | 1         | $f_j(1) + 4$  | $3f_j(1) + f_j(2) + 6$ | $3f_j(1) + 2f_j(2) + f_j(3) + 4$ | $f_j(1) + f_j(2) + f_j(3) + f_j(4) + 1$ | … |
| …      | …         | …             | …             | …             | …             | … |

The maximum number of existing services in the next time cycle.