Distributed Resource Allocation Policy for Network Slicing with Inter-operator Bandwidth Borrowing

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Abstract. Network slicing is a novel technology to effectively provide solutions for heterogeneous mobile service requirements in 5G network. Meanwhile, the shortage of spectrum resources becomes more severe with massive access requirement of Internet-of-Things (IoT) applications. In this paper, we study how to allocate spectrum resources to satisfy the diversified traffic requirements with network slicing and improve the utilization of spectrum resources. A spectrum resource allocation model with three layers is considered, including operator layer, slice layer and user layer. At the mobile operator layer, mobile operators can borrow frequency bandwidth from one another to improve the spectrum efficiency. Then, the mobile operator allocates its frequency bandwidth to the slices according to users' demand. At last, the slice assigns bandwidth to users. A network utility maximization problem is formulated and a distributed resource allocation algorithm is proposed based on alternating direction method of multipliers (ADMM). Simulation results show that the proposed algorithm

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can quickly converge to the optimal solution. In addition, the overall network utility can be effectively improved by lending or borrowing spectrum resources among operators. By adding the slice layer, the network can meet different types of service requirements.

Keywords: Spectrum leasing · Network slicing · Alternating direction method of multipliers (ADMM)

1 Introduction

The fifth generation (5G) wireless networks are envisioned to interconnect a massive number of miscellaneous end devices (e.g., smartphones, remote monitoring sensors, and home appliances) generating both mobile broadband data and machine-to-machine (M2M) services/applications (e.g., video conferencing, remote monitoring, and smart homing), to realize the ubiquitous Internet-of-Things (IoT) architecture [10]. Therefore, the communication networks must be able to adapt to different application scenarios. However, the traditional communication network mainly serves the mobile broadband users, and cannot adapt to the diversified traffic requirements of 5G in the future. A promising approach to address this need is the novel concept of network slicing, which aims at allocating portions of network resources to specific tenants, such as enhanced mobile broadband (eMBB), IoT, e-health, etc [9]. In [8], network slices were defined as end-to-end (E2E) logical networks running on a common underlying (physical or virtual) network with independent control and management. Such networks can simultaneously accommodate diverse business-driven use cases from multiple players, and hence it can solve the problem of multi-scenario services in 5G.

The appearance of multi-scenario services in 5G triggers the increasing demand of spectrum resources, which however, are limited due to the scarcity of frequency bands. How to improve resource utilization in a sliced network to meet the requirement of multi-scenario services is an urgent challenging problem to be solved. Nowadays, the resource allocation problem in network slicing system has attracted a lot of research interests from both academia and industry. The authors in [5] introduced a slicing plane for radio access network to enable innovative sharing of network resources. However, the resource allocation in [5] is a static solution, which can not adapt to the dynamics of slicing. Flexible slicing design is presented in [4] and [3]. The proposed algorithm flexibly shares the radio resources among multiple tenants, but does not consider the different service requirements of slices. In [7], an IoT-oriented architecture was proposed to enable the IoT applications and services with diverse requirements based on dynamic 5G slice allocation. And in [6], a dynamic wireless resource allocation scheme considering the different service requirements of slices was proposed. Besides, a dynamic slicing and trading framework is developed in [1] that not only determines the size of the network resource slices required for various active services, but also adapts resource prices in accordance with the microeconomic laws of supply and demand. However, the exist works do not take into account the shortage of spectrum resources and the spectrum resources owned by mobile operators are static.

In this paper, we consider a resource allocation problem in a network slicing system. The spectrum resources are owned by different mobile operators in a communication network. Unlike previous works, to deal with the shortage of spectrum resources, we assume that the spectrum bandwidth can be borrowed among mobile operators. When the spectrum resource of a certain mobile operator is abundant and while the others are in short supply, the utilization of spectrum resources can be improved by spectrum leasing. Meanwhile, mobile operators are motivated to lend spectrum resources to increase their incomes by charging the borrowed spectrum. Then, the mobile operator allocates spectrum resources to the slice according to traffic requirements. In order to solve the problem of spectrum leasing and resource allocation among multiple operators, a distributed resource allocation algorithm is proposed based on alternating direction method of multipliers (ADMM) [2]. In this algorithm, the resource allocation policy is iteratively and distributively calculated by each mobile operator in the network slicing system. Simulation results illustrate the efficiency of the proposed algorithm.

2 System Model and Problem Formulation

In this section, the system model is introduced and the optimization problem is formulated by jointly considering the spectrum resource leasing among mobile operators and spectrum resource allocation to slices and users. As shown in Fig. 1, the whole network can be divided into three layers: the mobile operator layer, the slice layer and the user layer. The mobile operator layer is in charge of allocating resources to slices, then the slice layer provides specific services to its users. Different from previous works, in order to improve the utilization of

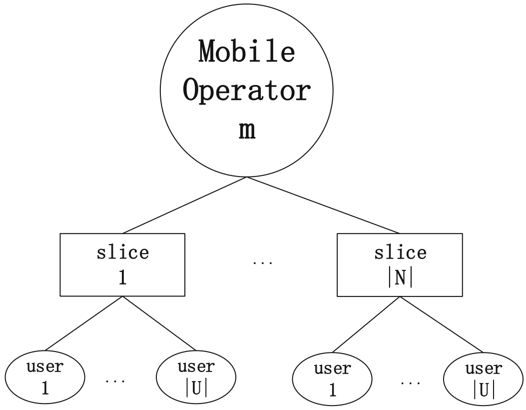

Fig. 1. Three layers of the network.

spectrum resources, we assume that the resource-lacked mobile operators can borrow spectrum bandwidth from other mobile operators.

Consider a set of mobile operators $\mathcal{M}$. At any given time, the mobile operator m ($m \in \mathcal{M}$) has a set of slices $\mathcal{N}_m$. Denote $\mathcal{U}_{n,m}$ as a set of users that belong to slice n ($n \in \mathcal{N}_m$). The total bandwidth that is owned by mobile operator m is B_m and the amount that mobile operator i borrows from mobile operator j is $q_{i,j}$ ($i, j \in \mathcal{M}, i \neq j$), therefore the total amount of available bandwidth of mobile operator m is

$$b_m = B_m - \sum_{i \neq m} q_{i,m} + \sum_{j \neq m} q_{m,j}, \tag{1}$$

where

$$\sum_{i \neq m} q_{i,m} \leq B_m. \tag{2}$$

Denote p_m as the price per unit of spectrum bandwidth lent by mobile operator m and C_m as the total budget of mobile operator m. The cost for borrowing spectrum from other mobile operators minus the income of lending spectrum to others should not exceed the total budget. We have

$$\sum_{j \neq m} q_{m,j} p_j - \sum_{i \neq m} q_{i,m} p_m \leq C_m. \tag{3}$$

Furthermore, the spectrum ratio of mobile operator m allocated to slice n is denoted by $f_{m,n}$ ($m \in \mathcal{M}, n \in \mathcal{N}_m$), where $0 \leq f_{m,n} \leq 1$. Likewise $0 \leq s_{m,n,u} \leq 1$ ($m \in \mathcal{M}, n \in \mathcal{N}_m, u \in \mathcal{U}_{m,n}$) represents the spectrum ratio of slice n allocated to user u. The spectrum efficiency of the user u ($u \in \mathcal{U}_{m,n}$) is

$$c_{m,n,u} = log_2(1 + SNR_{m,n,u}), \tag{4}$$

where $SNR_{m,n,u}$ is signal to noise ratio. The transmission rate of the user u ($u \in \mathcal{U}_{m,n}$) is

$$r_{m,n,u} = b_m f_{m,n} s_{m,n,u} c_{m,n,u}. \tag{5}$$

Denote $L_{m,n}$ as the service requirement of users in slice n of operator m, then we have

$$r_{m,n,u} \geq L_{m,n}. \tag{6}$$

The overall network utility is defined as

$$W = \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}_m} \sum_{u \in \mathcal{U}_{m,n}} log_2(r_{m,n,u}). \tag{7}$$

We aim to maximize the overall network utility while satisfying users' requirements and operators' cost constraint. The problem is formulated as

$$\max_{q_{m,j}, f_{m,n}, s_{m,n,u}} \quad W \tag{8a}$$

subject to

$$\sum_{j \neq m} q_{m,j} p_j - \sum_{i \neq m} q_{i,m} p_m \leq C_m, \quad \forall m, \tag{8b}$$

$$r_{m,n,u} \geq L_{m,n}, \quad \forall m, n, u, \tag{8c}$$

$$\sum_{u \in \mathcal{U}_{m,n}} s_{m,n,u} \leq 1, \quad \forall m, n, \tag{8d}$$

$$s_{m,n,u} \geq 0, \quad \forall m, n, u, \tag{8e}$$

$$\sum_{n \in \mathcal{N}_m} f_{m,n} \leq 1, \quad \forall m, \tag{8f}$$

$$f_{m,n} \geq 0, \quad \forall m, n, \tag{8g}$$

$$\sum_{i \neq m} q_{i,m} < B_m, \quad \forall m, \tag{8h}$$

$$q_{m,j} \geq 0, \quad \forall m, \ j \neq m. \tag{8i}$$

3 ADMM-Based Distributed Resource Allocation

The problem (8) is a convex problem, therefore lots of classical algorithms can solve this problem, such as simplex method and lagrangian multiplier method. However, these methods are all centralized, which are not suitable for our problem as mobile operators make divisions individually based on their own benefits and costs. Therefore, we consider a distributed algorithm to solve problem (8).

The alternating direction method of multipliers (ADMM) is a powerful tool that is well suitable for distributive convex optimization. It takes the form of a decomposition-coordination procedure, in which the solutions to small local subproblems are coordinated to find a solution to a large global problem [2]. To apply ADMM algorithm, we rewrite the problem as a standard minimization problem. It's obvious that to maximize the utility of network, (8d) and (8f) must be satisfied with equality. Hence, the problem can be rewritten as follows

$$\min_{q_{m,j}, f_{m,n}, s_{m,n,u}} - \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}_m} \sum_{u \in \mathcal{U}_{m,n}} log_2(b_m f_{m,n} s_{m,n,u} c_{m,n,u}) \tag{9a}$$

subject to

$$\sum_{u \in \mathcal{U}_{m,n}} s_{m,n,u} = 1, \quad \forall m, n, \tag{9b}$$

$$\sum_{n \in \mathcal{N}_m} f_{m,n} = 1, \quad \forall m, \tag{9c}$$

$$\sum_{j \neq m} q_{m,j} p_j - \sum_{i \neq m} q_{i,m} p_m \leq C_m, \quad \forall m, \tag{9d}$$

$$r_{m,n,u} \geq L_{m,n}, \quad \forall m, n, u, \tag{9e}$$

$$\sum_{i \neq m} q_{i,m} < B_m, \quad \forall m, \tag{9f}$$

$$q_{m,j} \geq 0, \quad \forall m, \ j \neq m, \tag{9g}$$

$$s_{m,n,u} \geq 0, \quad \forall m, n, u, \tag{9h}$$

$$f_{m,n} \geq 0, \quad \forall m, n. \tag{9i}$$

By adding complement variables and penalties, the augmented problem of (9) can be given as follows

$$\begin{aligned}
\min_{\substack{q_{m,j},\, f_{m,n},\, s_{m,n,u} \\ x_m,\, y_{m,n,u},\, z_m \\ u_{m,j},\, v_{m,n,u},\, w_{m,n}}} \ & - \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}_m} \sum_{u \in \mathcal{U}_{m,n}} log_2(b_m f_{m,n} s_{m,n,u} c_{m,n,u}) \\
& + \frac{\rho}{2} \Big[\sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}_m} \big(\sum_{u \in \mathcal{U}_{m,n}} s_{m,n,u} - 1 \big)^2 + \sum_{m \in \mathcal{M}} \big(\sum_{n \in \mathcal{N}_m} f_{m,n} - 1 \big)^2 \\
& + \sum_{m \in \mathcal{M}} \big(\sum_{i \neq m} q_{i,m} - B_m + z_m \big)^2 + \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}_m} \sum_{u \in \mathcal{U}_{m,n}} (s_{m,n,u} - v_{m,n,u})^2 \\
& + \sum_{m \in \mathcal{M}} \big(\sum_{j \neq m} q_{m,j} p_j - \sum_{i \neq m} q_{i,m} p_m - C_m + x_m \big)^2 + \sum_{m \in \mathcal{M}} \sum_{j \neq m} (q_{m,j} - u_{m,j})^2 \\
& + \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}_m} \sum_{u \in \mathcal{U}_{m,n}} (r_{m,n,u} - L_{m,n} - y_{m,n,u})^2 + \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}_m} (f_{m,n} - w_{m,n})^2 \Big]
\end{aligned} \tag{10a}$$

subject to

$$\sum_{u \in \mathcal{U}_{m,n}} s_{m,n,u} = 1, \quad \forall m, n, \tag{10b}$$

$$\sum_{n \in \mathcal{N}_m} f_{m,n} = 1, \quad \forall m, \tag{10c}$$

$$\sum_{j \neq m} q_{m,j} p_j - \sum_{i \neq m} q_{i,m} p_m - C_m + x_m = 0, \quad \forall m, \tag{10d}$$

$$r_{m,n,u} - L_{m,n} - y_{m,n,u} = 0, \quad \forall m, n, u, \tag{10e}$$

$$\sum_{i \neq m} q_{i,m} - B_m + z_m = 0, \quad \forall m, \tag{10f}$$

$$q_{m,j} - u_{m,j} = 0, \quad \forall m, \ j \neq m, \tag{10g}$$

$$s_{m,n,u} - v_{m,n,u} = 0, \quad \forall m, n, u, \tag{10h}$$

$$f_{m,n} - w_{m,n} = 0, \quad \forall m, n. \tag{10i}$$

where $\rho > 0$ is the penalty parameter and x_m, $y_{m,n,u}$, z_m, $u_{m,j}$, $v_{m,n,u}$, $w_{m,n}$ ($m \in \mathcal{M}$, $n \in \mathcal{N}_m$, $u \in \mathcal{U}_{m,n}$) are slack variables.

The dual problem of (10) is given as follows

$$\begin{aligned}
&\max_{\substack{a_{m,n},\, d_m,\, e_m,\, g_{m,n,u}\\ h_m,\, k_{m,j},\, l_{m,n,u},\, t_{m,n}}} \Bigg\{ \min_{\substack{q_{m,j},\, f_{m,n},\, s_{m,n,u}\\ x_m,\, y_{m,n,u},\, z_m\\ u_{m,j},\, v_{m,n,u},\, w_{m,n}}} -\sum_{m\in\mathcal{M}}\sum_{n\in\mathcal{N}_m}\sum_{u\in\mathcal{U}_{m,n}} log_2(b_m f_{m,n} s_{m,n,u} c_{m,n,u})\\
&+\frac{\rho}{2}\Bigg[\sum_{m\in\mathcal{M}}\sum_{n\in\mathcal{N}_m}\Big(\sum_{u\in\mathcal{U}_{m,n}} s_{m,n,u}-1\Big)^2+\sum_{m\in\mathcal{M}}\Big(\sum_{n\in\mathcal{N}_m} f_{m,n}-1\Big)^2\\
&+\sum_{m\in\mathcal{M}}\Big(\sum_{i\neq m} q_{i,m}-B_m+z_m\Big)^2+\sum_{m\in\mathcal{M}}\sum_{n\in\mathcal{N}_m}\sum_{u\in\mathcal{U}_{m,n}}(s_{m,n,u}-v_{m,n,u})^2\\
&+\sum_{m\in\mathcal{M}}\Big(\sum_{j\neq m} q_{m,j}p_j-\sum_{i\neq m} q_{i,m}p_m-C_m+x_m\Big)^2+\sum_{m\in\mathcal{M}}\sum_{j\neq m}(q_{m,j}-u_{m,j})^2\\
&+\sum_{m\in\mathcal{M}}\sum_{n\in\mathcal{N}_m}\sum_{u\in\mathcal{U}_{m,n}}(r_{m,n,u}-L_{m,n}-y_{m,n,u})^2+\sum_{m\in\mathcal{M}}\sum_{n\in\mathcal{N}_m}(f_{m,n}-w_{m,n})^2\Bigg]\\
&+\sum_{m\in\mathcal{M}} e_m\Big(\sum_{j\neq m} q_{m,j}p_j-\sum_{i\neq m} q_{i,m}p_m-C_m+x_m\Big)\\
&+\sum_{m\in\mathcal{M}}\sum_{n\in\mathcal{N}_m}\sum_{u\in\mathcal{U}_{m,n}} g_{m,n,u}(r_{m,n,u}-L_{m,n}-y_{m,n,u})\\
&+\sum_{m\in\mathcal{M}} h_m\Big(\sum_{i\neq m} q_{i,m}-B_m+z_m\Big)+\sum_{m\in\mathcal{M}}\sum_{m\neq j} k_{m,j}(q_{m,j}-u_{m,j})\\
&+\sum_{m\in\mathcal{M}}\sum_{n\in\mathcal{N}_m} a_{m,n}\Big(\sum_{u\in\mathcal{U}_{m,n}} s_{m,n,u}-1\Big)+\sum_{m\in\mathcal{M}} d_m\Big(\sum_{n\in\mathcal{N}_m} f_{m,n}-1\Big)\\
&+\sum_{m\in\mathcal{M}}\sum_{n\in\mathcal{N}_m}\sum_{u\in\mathcal{U}_{m,n}} l_{m,n,u}(s_{m,n,u}-v_{m,n,u})+\sum_{m\in\mathcal{M}}\sum_{n\in\mathcal{N}_m} t_{m,n}(f_{m,n}-w_{m,n})\Bigg\}
\end{aligned} \tag{11}$$

where $a_{m,n},\ d_m,\ e_m,\ g_{m,n,u},\ h_m,\ k_{m,j},\ l_{m,n,u},\ t_{m,n}$ $(m \in \mathcal{M},\ n \in \mathcal{N}_m,\ u \in \mathcal{U}_{m,n})$ are dual variables. In addition, we define $\mathbf{Q}_m = \big(q_{m,1},\cdots,0,\cdots,q_{m,M}\big)^T$ with only the m-th element being zero to represent the resource array of mobile operator m borrowing from other mobile operators. And $\mathbf{Q'}_m = \big(q_{1,m},\cdots,0,\cdots,q_{M,m}\big)^T$ with the m-th elements being zero to represent the resource array that mobile operator m lends to other operators. We have

$$\big(\mathbf{Q}_1^T,\mathbf{Q}_2^T,\cdots,\mathbf{Q}_M^T\big)^T=\big(\mathbf{Q'}_1\ \mathbf{Q'}_2\cdots\mathbf{Q'}_M\big). \tag{12}$$

As each operator decides the amount of resource borrowed from others distributively, $\mathbf{Q}_m$ will be updated in each subproblem. Then, by (12), $\mathbf{Q'}_m$ will be updated by sharing information among operators.

Let $\mathbf{F}_m = \big(f_{m,1},f_{m,2},\cdots,f_{m,N}\big)^T$, $\mathbf{P}_m = \big(p_1,p_2,\cdots,p_m\big)^T$ and $\mathbf{S}_m = \begin{pmatrix} s_{m,1,1} & \cdots & s_{m,1,U}\\ \vdots & \ddots & \vdots\\ s_{m,N,1} & \cdots & s_{m,N,U}\end{pmatrix}$. To apply ADMM algorithm to solve the problem distributively, we decompose the minimization problem into $|\mathcal{M}|$ subproblems. In particular, each operator optimizes $\mathbf{Q}_m,\ \mathbf{F}_m,\ \mathbf{S}_m$ by solving the following subproblem separately.

$$
\begin{aligned}
(\mathbf{Q}_m^{(k+1)}, \mathbf{F}_m^{(k+1)}, \mathbf{S}_m^{(k+1)}) = arg\Big\{ &\min_{\mathbf{Q}_m,\mathbf{F}_m,\mathbf{S}_m} - \sum_{n\in\mathcal{N}_m}\sum_{u\in\mathcal{U}_{m,n}} log_2(b_m^{(k)} f_{m,n} s_{m,n,u} c_{m,n,u}) \\
&+ \frac{\rho}{2}\Big[(\sum_{i\neq m} q_{i,m}^{(k)} - B_m + z_m^{(k)})^2 + \sum_{n\in\mathcal{N}_m}\big(\sum_{u\in\mathcal{U}_{m,n}} s_{m,n,u} - 1\big)^2 \\
&+ (\mathbf{Q}_m^T\mathbf{P} - \sum_{i\neq m} q_{i,m}^{(k)} p_m - C_m + x_m^{(k)})^2 + \sum_{j\neq m}(q_{m,j}^{(k)} - u_{m,j}^{(k)})^2 \\
&+ \sum_{n\in\mathcal{N}_m}\sum_{u\in\mathcal{U}_{m,n}} (r_{m,n,u}^{(k)} - L_{m,n} - y_{m,n,u}^{(k)})^2 + \big(\sum_{n\in\mathcal{N}_m} f_{m,n} - 1\big)^2 \\
&+ \sum_{n\in\mathcal{N}_m}\sum_{u\in\mathcal{U}_{m,n}} (s_{m,n,u}^{(k)} - v_{m,n,u}^{(k)})^2 + \sum_{n\in\mathcal{N}_m}(f_{m,n}^{(k)} - w_{m,n}^{(k)})^2\Big] \\
&+ e_m^{(k)}(\sum_{i\neq m} q_{i,m}^{(k)} p_m - \sum_{j\neq m} q_{m,j}^{(k)} p_j - C_m + x_m^{(k)}) \\
&+ \sum_{n\in\mathcal{N}_m}\sum_{u\in\mathcal{U}_{m,n}} g_{m,n,u}^{(k)}(r_{m,n,u}^{(k)} - L_{m,n} - y_{m,n,u}^{(k)}) \\
&+ h_m^{(k)}(\sum_{i\neq m} q_{i,m}^{(k)} - B_m + z_m^{(k)}) + \sum_{j\neq m} k_{m,j}^{(k)}(q_{m,j}^{(k)} - u_{m,j}^{(k)}) \\
&+ \sum_{n\in\mathcal{N}} a_{m,n}^{(k)}(\sum_{u\in\mathcal{U}_{m,n}} s_{m,n,u}^{(k)} - 1) + \sum_{n\in\mathcal{N}_m} t_{m,n}^{(k)}(f_{m,n}^{(k)} - w_{m,n}^{(k)}) \\
&+ \sum_{n\in\mathcal{N}_m}\sum_{u\in\mathcal{U}_{m,n}} l_{m,n,u}^{(k)}(s_{m,n,u}^{(k)} - v_{m,n,u}^{(k)}) + d_m^{(k)}(\sum_{n\in\mathcal{N}_m} f_{m,n}^{(k)} - 1)\Big\}
\end{aligned}
\tag{13}
$$

After the matrix $\mathbf{Q}_m$ is update, the matrix $\mathbf{Q'}_m$ can be updated by the mobile operators sharing how much bandwidth to be borrowed with one another. Later, each operator solves the following problems distributively to update the slack variables:

$$x_m^{(k+1)} = arg\min_{x_m} \frac{\rho}{2}((\mathbf{Q}_m^{(k+1)})^T\mathbf{P} - (\mathbf{Q'}_m^{(k+1)})^T\mathbf{P} - C_m + x_m)^2 + e_m^{(k)} x_m \tag{14a}$$

$$y_{m,n,u}^{(k+1)} = arg\min_{y_{m,n,u}} \frac{\rho}{2}(r_{m,n,u}^{(k+1)} - L_{m,n} - y_{m,n,u})^2 - g_{m,n,u}^{(k)} y_{m,n,u} \tag{14b}$$

$$z_m^{(k)} = arg\min_{z_m} \frac{\rho}{2}(\sum_{i\neq m} q_{i,m}^{(k+1)} - B_m + z_m)^2 + h_m^{(k)} z_m \tag{14c}$$

$$u_{m,j}^{(k+1)} = arg\min_{u_{m,j}} \frac{\rho}{2}(q_{m,j}^{(k+1)} - u_{m,j})^2 - k_{m,j}^{(k)} u_{m,j} \tag{14d}$$

$$v_{m,n,u}^{(k+1)} = arg\min_{v_{m,n,u}} \frac{\rho}{2}(s_{m,n,u}^{(k+1)} - v_{m,n,u})^2 - l_{m,n,u}^{(k)} v_{m,n,u} \tag{14e}$$

$$w_{m,n}^{(k+1)} = arg\min_{w_{m,n}} \frac{\rho}{2}(f_{m,n}^{(k+1)} - w_{m,n})^2 - t_{m,n}^{(k)} w_{m,n} \tag{14f}$$

In the end, the dual variables are also updated distributively:

$$a_{m,n}^{(k+1)} = a_{m,n}^{(k)} + \rho(\sum_{u \in \mathcal{U}} s_{m,n,u}^{(k+1)} - 1) \tag{15a}$$

$$d_m^{(k+1)} = d_m^{(k)} + \rho(\sum_{n \in \mathcal{N}} f_{m,n}^{(k+1)} - 1) \tag{15b}$$

$$e_m^{(k+1)} = e_m^{(k)} + \rho((\mathbf{Q}_m^{(k+1)})^T\mathbf{P} - (\mathbf{Q'}^{(k+1)})^T\mathbf{P} - C_m + x_m) \tag{15c}$$

$$g_{m,n,u}^{(k+1)} = g_{m,n,u}^{(k)} + \rho(r_{m,n,u}^{(k+1)} - L_{m,n} - y_{m,n,u}^{(k+1)}) \tag{15d}$$

$$h_m^{(k+1)} = h_m^{(k)} + \rho(\sum_{i \neq m} q_{i,m}^{(k+1)} - B_m + z_m^{(k+1)}) \tag{15e}$$

$$k_{m,j}^{(k+1)} = k_{m,j}^{(k)} + \rho(q_{m,j}^{(k+1)} - u_{m,j}^{(k+1)}) \tag{15f}$$

$$l_{m,n,u}^{(k+1)} = l_{m,n,u}^{(k)} + \rho(s_{m,n,u}^{(k+1)} - v_{m,n,u}^{(k+1)}) \tag{15g}$$

$$t_{m,n}^{(k+1)} = t_{m,n}^{(k)} + \rho(f_{m,n}^{(k+1)} - w_{m,n}^{(k+1)}) \tag{15h}$$

In summary, the algorithm is given as Algorithm 1.

Algorithm 1. Proposed ADMM-based Resource Allocation Algorithm

1: Fix a penalty parameter $\rho > 0$; Initialize $q_{m,j}^{(0)}$, $f_{m,n}^{(0)}$, $s_{m,n,u}^{(0)}$, $x_m^{(0)}$, $y_{m,n,u}^{(0)}$, $z_m^{(0)}$, $u_{m,j}^{(0)}$, $v_{m,n,u}^{(0)}$, $w_{m,n}^{(0)}$ $a_{m,n}^{(0)}$, $d_m^{(0)}$, $h_m^{(0)}$, $k_{m,j}^{(0)}$, $l_{m,n,u}^{(0)}$, $t_{m,n}^{(0)}$; Set k=0;
2: **repeat**
3: Each operator updates $\mathbf{Q}_m^{(k+1)}$, $\mathbf{F}_m^{(k+1)}$, $\mathbf{S}_m^{(k+1)}$ according to (13);
4: Each operator m propose its intended amount of bandwidth $q_{m,j}^{(k+1)}$ to borrow to every other operator j to update $\mathbf{Q'}_m^{(k+1)}$
5: Each operator updates slack variables $x_m^{(k+1)}$, $y_{m,n,u}^{(k+1)}$, $z_m^{(k+1)}$, $u_{m,j}^{(k+1)}$, $v_{m,n,u}^{(k+1)}$, $w_{m,n}^{(k+1)}$ according to (14)
6: Each operator updates dual variables $a_{m,n}^{(k+1)}$, $d_m^{(k+1)}$, $h_m^{(k+1)}$, $k_{m,j}^{(k+1)}$, $l_{m,n,u}^{(k+1)}$, $t_{m,n}^{(k+1)}$ accroding to (15)
7: $k := k + 1$
8: **until** a predefined convergence criterion is satisfied.

In this algorithm, each operator firstly determines whether to borrow bandwidth from others according to their own spectrum bandwidth and users' requirements and updates $\mathbf{Q}_m$. Then, each operator allocates bandwidth to its slices and users and updates $\mathbf{F}_m$ and $\mathbf{S}_m$. After $\mathbf{Q}_m$ is updated, mobile operators tell one another how much bandwidth is needed to be borrowed. Thus, $\mathbf{Q'}_m$ is updated according. Next, each mobile operator updates slack variables and dual variables according to (14) and (15). Since the problem is convex, the optimality of the proposed algorithm can be guaranteed. Therefore, by iterating until a predefined convergence criterion is satisfied, the maximum network utility can be obtained.

4 Simulation Results

In this section, the performance of the proposed algorithm is evaluated by simulations. In our simulations, each operator has 2 slices and each slice has 2 active users. The rate requirements specified by users in slicing are referred to [1]. The simulation parameters are listed in the Table 1.

Table 1. Simulation parameters and values

Mobile operator	1	2	3	4
Spectrum bandwidth	50 MHz	20 MHz	50 MHz	20 MHz
The price per unit of spectrum	15	30	15	20
The limitation of cost	200	150	200	300
Service requirement of users in slice 1	20 MHz	10 MHz	15 MHz	60 MHz
Service requirement of users in slice 2	1 MHz	40 MHz	30 MHz	1 MHz

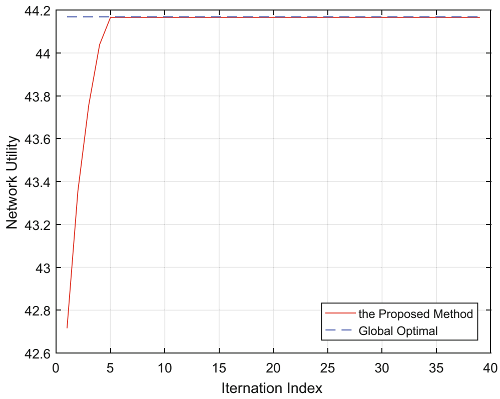

Fig. 2. The optimal network utility of the proposed method versus iterations, $|\mathcal{M}| = 2$.

The optimal network utility of the system versus iterations is depicted in Figs. 2 and 3, with 2 and 4 operators respectively. Simulation parameters of Fig. 2 are based on mobile operator 1 and 2 in Table 1. In order to evaluate the performance of proposed algorithm, the global optimal solution of problem (8) is given for comparison. According to Figs. 2 and 3, we can see that the proposed algorithm can achieve the global optimal solution quickly. When there are 2 operators in the system, the proposed method converges in 5 iterations. When there are 4 operators in the system, the proposed method needs 9 iterations to converge.

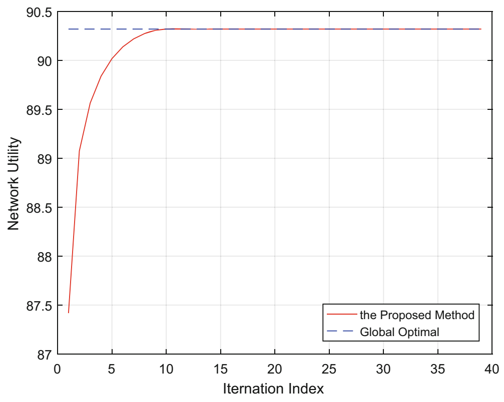

Fig. 3. The optimal network utility of the proposed method versus iterations, $|\mathcal{M}| = 4$.

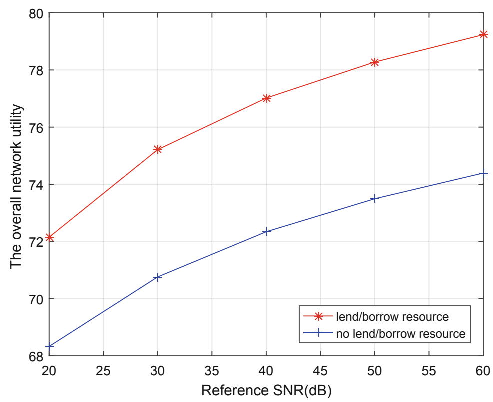

Fig. 4. The optimal network utility with and without spectrum resource leasing versus reference SNR.

The optimal network utility when there is no spectrum leasing between operators is also compared, as shown in Fig. 4. As can be seen that with the increasing of SNR, the network utility of the system enabling spectrum resource leasing changes from 72 to 79. However, without spectrum resource leasing, the network utility of the system only change from 68 to 74.2. It validates that when there are operators lacking of spectrum resources, our model can effectively solve the problem and improve the network efficiency.

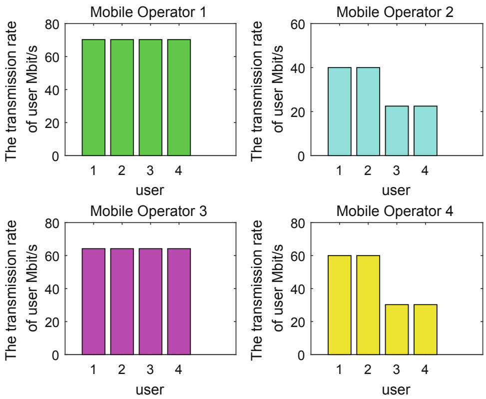

Fig. 5. The users'data rate with the proposed algorithm.

The users' data rates are shown in Fig. 5. Comparing with the service requirements specified by the slices in Table 1, it can be seen that the transmission rates of users of each mobile operator meet the service requirements specified in the slices. Among them, mobile operators 1 and 3 have adequate spectrum resources. In order to achieve maximum network utility, their bandwidth is evenly allocated to each slice, then each slice allocates resources to its users evenly. Therefore, the users' transmission rates of different slices are the same. Mobile operators 2 and 4, however, do not have sufficient spectrum resources to meet the service requirements, so they borrow spectrum resources from operator 1 and 3. In order to maximize network utility, the slices allocate the spectrum resources to users equally. Therefore, the proposed model can effectively adapt to various service requirements in 5G.

5 Conclusion

In this paper, a network utility maximization problem is formulated and solved by a distributed resources allocation method based on ADMM in a three-layer network consisting of mobile operator layer, slicing layer and user layer. As the problem is convex, the optimality of the proposed algorithm can be guaranteed. By comparing with the global optimal solution, simulations validate the effectiveness and optimality of the proposed algorithm. Meanwhile, on the premise that spectrum resources between operators can be rented, the network spectrum utilization has been significantly improved, and the users' data rates can be guaranteed through network slicing.

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