Resource Joint Allocation Scheme Based on Network Slicing Under C-RAN Architecture

Jiajia Chen[1], Jie Gong[2], Xiang Chen[1](✉), and Terngyin Hsu[3]

[1] School of Electronics and Information Technology, Sun Yat-sen University, Guangzhou 510006, China
chenxiang@mail.sysu.edu.cn

[2] School of Data and Computer Science, Sun Yat-sen University, Guangzhou 510006, China

[3] Department of Computer Science, National Chiao Tung University, Hsinchu, Taiwan

Abstract. The upcoming 5G system is considered not only can meet the demand of various services, but also solve the problem that data will grow explosively. Therefore, we need a viable network architecture to support various service demand and realize resources allocation flexibly. C-RAN was considered to be a promising 5G network architecture. And network slicing, which as a promising technology, can provides customized service according to the various business scenarios of 5G. This paper proposed a joint resources allocation scheme of network slicing that based on C-RAN. The scheme not only combine network slicing with C-RAN, but also solve the problem of joint spectrum and computing resource allocation. This paper model the problem into a MINLP problem. Based on the characteristics of the model, the problem will be decomposed into two subproblems respectively to be solved. In order to verify the proposed model, the other two joint resource allocation scheme will be introduced to compare. The simulation results also illustrate the effectiveness of the proposed scheme.

Keywords: Network slicing · Cloud Radio Access Network (C-RAN) · Resource allocation

1 Introduction

In recent years, the exponential growth in mobile data traffic has been triggered by the increasing use of mobile devices [7]. In addition, 5G not only continue to

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provide stable and high-quality services for traditional mobile communication, but also provide services for other emerging communication types(e.g.., video conferencing, remote monitoring, and smart homing). Besides, different communication typies have different communication requirements. As a promising technology, network slicing is an end-to-end logical network provisioned with a set of isolated virtual resources on the shared physical infrastructure [5]. Through network slicing technology, operators can flexibly and dynamically allocate network resources into logical network slicing according to users' needs, so as to provide services for different types of businesses. However, the deployment of network slicing requires a flexible and programmable physical network architecture, and Cloud Radio Access Network (C-RAN) is a flexible and programmable physical network architecture.

A typical structure of C-RAN includes three main components: Remote Radio Heads (RRHs), fronthaul links, and Baseband Unit (BBU) pool [9]. RRH is responsible for receiving and transmitting wireless signals, and BBU is responsible for baseband processing. Different from the traditional network architecture, in C-RAN, BBU will be decoupled from RRH and concentrated together to form a BBU resource pool. By decoupling RRH and BBU, resource scheduling can be more flexible and network capacity can be improved. By pooling the BBUs together to form a BBU pool, Capital Expenditure (CAPEX) and Operating Expense (OPEX) can be reduced. Moreover, the fronthaul link connecting RRH and BBU pool is usually make up of high-capacity and low-delay optical fiber, which can significantly improve the network efficiency and spectral efficiency. Based on these advantages, C-RAN has become a prospective architecture for 5G. Therefore, this paper combined the network slicing technique with C-RAN.

The most significant advantage of the C-RAN network architecture is the sharing of resources by pooling the BBU together to form a BBU pool. [11] has designed a joint dynamic radio clustering and cooperative beamforming scheme that maximizes the downlink weighted sum-rate system utility. [6] aims at minimizing the system power consumption by jointly allocating the computing and radio resource under the outage Quality of Service (QoS) constraint. Besides, there are many studies on C-RAN and network slicing. [2] has instantiated the network slice under C-RAN by making use of the Open Air Interface (OAI) platform and a specific Software Defined Network (SDN) controller. In addition, in [3,10,14], the resource optimization problem of network slices under the c-ran network architecture is studied. [3] have study the joint optimal deployment of network slicing and the allocation of computational resources in a hybrid C-RAN architecture by taking into account the requirements of the 5G services and the characteristics of the cloud nodes. In [10], it incorporated two typical 5G services, i.e., enhanced Mobile Broadband (eMBB) and ultra-Reliable Low-Latency Communications (uRLLC), in a C-RAN, which is suitable for RAN slicing due to its high flexibility. [14] propose a two-timescale resource management scheme for network slicing in C-RAN, aiming at maximizing the profit of a tenant.

Based on the C-RAN network architecture, this paper proposes a joint allocation scheme of network slicing. The scheme integrates network slicing technology into the C-RAN network architecture and considers the joint allocation of spectrum resources and computing resources in network slicing. What's more, the joint allocation of spectrum resources and computing resources will be modeled as a Mixed-Integer Nonlinear Programming (MINLP) problem, which not only takes into account the different requirements of different types of slices, but also takes into account the limitation of transmission rate of fronthaul link in C-RAN. Based on the characteristics of the proposed scheme, the problem will be decomposed into two subproblems respectively to solved. What's more, two joint resource scheme will be introduced to varify the effectiveness of the proposed scheme. The simulation results show that the proposed scheme can achieve better resource utilization than the other two schemes, thus verifying the effectiveness of the proposed scheme.

2 System Model and Problem Formulation

As shown in Fig. 1, it is assumed that in C-RAN network, there is a BBU pool and several RRHs with a set of $\mathcal{K}$. And the RRHs are distributed in an area with coverage range of R. In the system, the set of total users is $\mathcal{U}$, and the set of slices is $\mathcal{N}$. What's more, the set of users of slice n ($n \in \mathcal{N}$) is $\mathcal{U}_n$, and we have $\sum_{n\in\mathcal{N}} \mathcal{U}_n = \mathcal{U}$. In addition, we define the set of users that connect to RRH

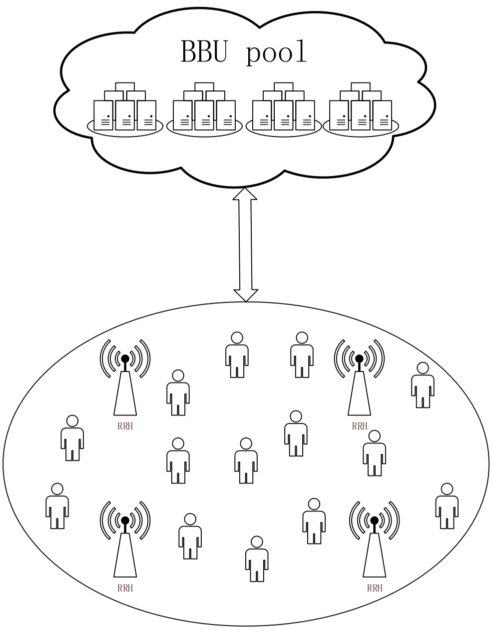

Fig. 1. The system model

k ($k \in \mathcal{K}$) is $\mathcal{U}_k$, and we have $\sum_{k \in \mathcal{K}} \mathcal{U}_k = \mathcal{U}$. Besides, we suppose that the total bandwidth in the network is B, the total computing resources are C, and the limitation of transmission rate of RRH k and the fronthaul link is F_k.

2.1 The Communication Quality Standard of Network Slicing

In this paper, we choose the minimum data transmission rate of users as the communication quality standard of network slicing. We assume that the user u of slice n will connect to the RRH k, then the signal-to-noise ratio (SINR) of the user u is $SINR_{k,u_n}$. According to paper [13], the SINR of user u is

$$SINR_{k,u_n} = \frac{p_k g_{k,u_n}}{\sum_{i \in k, i \neq k} p_i g_{i,u_n} + \sigma^2}, \tag{1}$$

where p_k is transmission power of RRH k, g_{k,u_n} is the channel gain between user k and RRH k, and σ^2 is the white Gaussian noise power. What's more, we assume that b_{k,u_n} is the spectrum resource that allocated to user u. Then according to the Shannon's formula, the spectrum efficiency of the user u is

$$d_{k,u_n} = log_2(1 + SINR_{k,u_n}). \tag{2}$$

Therefore, the data transmission rate of user u is

$$r_{k,u_n} = a_{k,u_n} b_{k,u_n} d_{k,u_n}, \tag{3}$$

where a_{k,u_n} indicates whether the user u has successfully accessed RRH k. If user u has accessed to the RRH k successfully, then $a_{k,u_n} = 1$, otherwise $a_{k,u_n} = 0$. By defining $r_{n_{min}}$ as the lowest data transmission rate that users of slice n have to satisfy, then we have

$$r_{k,u_n} \geq r_{n_{min}}. \tag{4}$$

2.2 The Mapping of Computing Resources and Spectrum Resources

The computing resources that consumed in the communication are positively correlated with the spectrum resources that consumed, so the relationship between computing resources and spectrum resources consumed in the system is defined as follow

$$B_{consume} = \omega C_{consume}, \tag{5}$$

where ω is constant. What's more, according to [11] and [8], the computing resources required by users increase with the growth of data transmission rate during the process communication. Therefore, we have

$$c_{k,u_u} = \phi(r_{k,u_n}), \tag{6}$$

where ϕ is a increasing function.

2.3 The Problem Formulation

In this paper, we aim to maximize the total resource utilization of the network and define the resource utilization as

$$\eta = \frac{r_{sum}}{B_{consume}} = \frac{r_{sum}}{\omega C_{consume}}. \tag{7}$$

Therefore, the resource utilization of this paper is

$$\eta = \frac{\sum_{k\in\mathcal{K}}\sum_{u\in\mathcal{U}_k} r_{k,u_n}}{\beta\sum_{k\in\mathcal{K}}\sum_{u\in\mathcal{U}_k} c_{k,u_n}}. \tag{8}$$

Because the target of this paper is maximizing the total resource utilization, the problem formulation can be expressed as

$$\max_{a_{k,u_n}, b_{k,u_n}, c_{k,u_n}} \eta, \tag{9}$$

s.t.

$$\sum_{k\in\mathcal{K}}\sum_{u\in\mathcal{U}_k} b_{k,u_n} \le B, \tag{9-1}$$

$$\sum_{k\in\mathcal{K}}\sum_{u\in\mathcal{U}_k} c_{k,u_n} \le C, \tag{9-2}$$

$$\sum_{u\in\mathcal{U}_k} r_{k,u_n} \le F_k, \forall k, \tag{9-3}$$

$$r_{k,u_n} \ge r_{n_{min}}, \forall u, \tag{9-4}$$

$$c_{k,u_u} \ge \phi(r_{k,u_n}), \forall u, \tag{9-5}$$

$$\sum_{k\in\mathcal{K}} a_{k,u_n} = 1, a_{k,u_n} \in \{0,1\}, \forall u. \tag{9-6}$$

Among them, the constraint (9-1) refers that the sum of bandwidth of all the user in the system can not be higher than the total bandwidth of system, constraint (9-2) refers that the sum of computing resource of all the user in the system is not higher than the amount of computing resources in the system, and constraints (9-3) refers that the user's total transmission rate of RRH is not higher than the limitation of the fronthual link. And constraint (9-6) refers that all the users can only connect to one RRH.

3 Joint Resource Allocation Algorithm Based on Network Slice

The problem (9) is a MINLP problem, which can be proved to be a NP-hand problem, so there is no deterministic algorithm to solve it. However, the problem (9) is a multi-variables optimization problem and the variables are correlated. The optimization results of the variables c_{k,u_n} are determined by the optimization results of the variables a_{k,u_n} and b_{k,u_n}. Therefore, this paper will decompose the optimization problem (9) into two sub-problems, including spectrum resource allocation problem and compute resource allocation problem. This two subproblems will be solved by appropriate algorithms respectively.

3.1 The Spectrum Resource Allocation Problem

At first, we assume that variable c_{k,u_n} has been known, then $\beta \sum_{u \in \mathcal{U}} c_{k,u_n}$ can be viewed as a constant. Therefore, the spectrum resource allocation problem can be separated from the problem (9) and expressed as

$$\max_{a_{k,u_n}, b_{k,u_n}} \sum_{k \in \mathcal{K}} \sum_{u \in \mathcal{U}_k} r_{k,u_n}, \tag{10}$$

s.t.

$$\sum_{k \in \mathcal{K}} \sum_{u \in \mathcal{U}_k} b_{k,u_n} \leq B, \tag{10-1}$$

$$\sum_{u \in \mathcal{U}_k} r_{k,u_n} \leq F_k, \forall k, \tag{10-2}$$

$$r_{k,u_n} \geq r_{n,min}, \forall u, \tag{10-3}$$

$$\sum_{k \in \mathcal{K}} a_{k,u_n} = 1, \forall u. \tag{10-4}$$

After decomposition, the subproblem is still a MINLP problem. If the exhaustive search method is used as the solution to this problem, the optimal allocation scheme of spectrum resources needs $|\mathcal{U}|^{|\mathcal{K}|}$ times. [12] has studied the nonconvex optimization of multicarrier system spectrum allocation problem. It has found that when the optimization problem satisfied time sharing conditions, even if the problem is a non-convex optimization problem, the optimum solution of original problem and its dual problem will be the same. Therefore, we apply dual decomposition to solve the spectrum resource allocation problem.

Firstly, the Lagrangian function of (10) is obtained as follows

$$\begin{aligned}
&L(a,b,\alpha,\beta,\gamma)\\
&=\sum_{k\in\mathcal{K}}\sum_{u\in\mathcal{U}_k} a_{k,u_n}b_{k,u_n}d_{k,u_n}+\alpha(B-\sum_{u\in\mathcal{U}}b_{k,u_n})\\
&+\sum_{k\in\mathcal{K}}\sum_{u\in\mathcal{U}_k}\gamma_{k,u_n}(a_{k,u_n}b_{k,u_n}c_{k,u_n}-r_{n,min})\\
&+\sum_{k\in\mathcal{K}}\beta_k(F_k-\sum_{u\in\mathcal{U}_k}a_{k,u_n}b_{k,u_n}d_{k,u_n})\\
&=\sum_{k\in\mathcal{K}}\sum_{u\in\mathcal{U}_k}[a_{k,u_n}(b_{k,u_n}d_{k,u_n}-\beta_k b_{k,u_n}d_{k,u_n}\\
&+\gamma_{k,u_n}b_{k,u_n}d_{k,u_n})-\alpha b_{k,u_n}]+\alpha B\\
&-\sum_{k\in\mathcal{K}}\sum_{u\in\mathcal{U}_k}\gamma_{k,u_n}r_{n,min}+\sum_{k\in\mathcal{K}}\beta_k F_k\\
&=\sum_{k\in\mathcal{K}}L_k(a_{k,u_n},b_{k,u_n},\alpha,\beta_k,\gamma_{k,u_n})+\alpha B\\
&+\sum_{k\in\mathcal{K}}\beta_k F_k-\sum_{k\in\mathcal{K}}\sum_{u\in\mathcal{U}_k}\gamma_{k,u_n}r_{n,min}
\end{aligned}\tag{11}$$

where α, β_k and η_{k,u_n} is the dual variables of the constraint in problem (10). What's more, we define

$$\begin{aligned}
&L_k(a,b,\alpha,\beta,\gamma)\\
&=\sum_{u\in\mathcal{U}_k}[a_{k,u_n}(b_{k,u_n}d_{k,u_n}-\beta_k b_{k,u_n}d_{k,u_n}+\gamma_{k,u_n}b_{k,u_n}d_{k,u_n})]-\alpha b_{k,u_n}.
\end{aligned}$$

Then, the dual problem of problem(10) is

$$\begin{aligned}
&\min\nolimits_{\alpha,\beta,\gamma} g(\alpha,\beta,\gamma)\\
&s.t\quad \alpha\geq 0,\beta\geq 0,\gamma\geq 0
\end{aligned}\tag{12}$$

For convenience, the dual problem can be expressed specifically as follow

$$\begin{aligned}
&g(\alpha,\beta,\gamma)\\
&=\max_{a,b}\sum_{k\in\mathcal{K}}L_k(a,b,\alpha,\beta,\gamma)-\sum_{k\in\mathcal{K}}\sum_{u\in\mathcal{U}_k}\gamma_{k,u_n}r_{n,min}+\alpha B+\sum_{k\in\mathcal{K}}\beta_k F_k
\end{aligned}\tag{13}$$

When the dual variable are known, $\gamma_{k,u_n}r_{n,min}$, αB and $\beta_k F_k$ can be viewed as constants. Thus, the dual problem can be decomposed into K sub-problems

$$\begin{aligned}
&g_k(\alpha,\beta,\gamma)\\
&=\max_{a,b}L_k(a,b,\alpha,\beta,\gamma)\\
&=\max_{a,b}\sum_{u\in\mathcal{U}_k}[a_{k,u_n}(b_{k,u_n}d_{k,u_n}-\beta_k b_{k,u_n}d_{k,u_n}+\gamma_{k,u_n}b_{k,u_n}d_{k,u_n})-\alpha b_{k,u_n}]
\end{aligned}\tag{14}$$

Assuming that user u will connect with RRH k, which means that $a_{k,u_n} = 1$, we can then obtain the optimal solution to the spectrum resource allocation problem from the following subproblems

$$\begin{aligned} \max_{b_{k,u_n}} \quad & \sum_{u \in \mathcal{U}_k} (b_{k,u_n} d_{k,u_n} - \beta_k b_{k,u_n} d_{k,u_n} + \eta_{k,u_n} b_{k,u_n} d_{k,u_n} - \alpha b_{k,u_n}) \\ s.t. \quad & b_{k,u_n} \geq 0 \end{aligned} \tag{15}$$

When the spectrum resources allocated to each user are determined, the user u can obtain the set of transmission rates $\mathbf{R}_{u_n} = \left[r_{1,u_n}, r_{2,u_n}, ..., r_{K,u_n} \right]$ that can be achieved for each RRH connection. According to $\mathbf{R}_{u_n}$, the user can then determine which RRH connection can obtain the maximum data transmission rate and determine a_{k,u_n}

$$a_{k,u_n} = \begin{cases} 1, & \text{if } r_{k,u_n} = arg \max_k \mathbf{R}_{u_n} \\ 0, & \text{else} \end{cases} \tag{16}$$

Finally, we update the dual varialbes by using subgradient method

$$\alpha^{t+1} = [\alpha^t - \rho_1^t (B - \sum_{k \in \mathcal{K}} \sum_{u \in \mathcal{U}_k} b_{k,u_n})]^+ \tag{17}$$

$$\beta_k^{t+1} = [\beta_k^t - \rho_2^t (F_k - \sum_{u \in \mathcal{U}_k} r_{k,u_n})]^+ \tag{18}$$

$$\gamma_{k,u_n}^{t+1} = [\gamma_{k,u_n}^t - \rho_3^t (r_{k,min} - r_{k,u_n})]^+ \tag{19}$$

where ρ_1^t, ρ_2^t and ρ_3^t are appropriate iteration step sizes.

3.2 The Computational Resource Allocation Problem

After the spectrum resource allocation problem is solved, the computational resource allocation problem can be expressed as follows

$$\begin{aligned} \min_{c_{k,u_n}} & \sum_{k \in \mathcal{K}} \sum_{u \in \mathcal{U}_k} c_{k,u_n} \\ s.t. & \sum_{k \in \mathcal{K}} \sum_{u \in \mathcal{U}_k} c_{k,u_n} \leq C \\ & c_{k,u_u} \geq \phi(r_{k,u_n}) \end{aligned} \tag{20}$$

It is clear that the computing resource allocation problem is a convex problem, so there are many ways to solve it. In this paper, we will use the mathematical tools CVX [1] to obtain the optimal solution. Because CVX is a powerful tool to solve the convex optimization problem. It can not only solve the linear programming standards such as quadratic programming problem, also can solve many other complex convex optimization problem.

3.3 The Summary of the Proposed Algorithm

According to the previous content, the algorithm proposed in this paper is shown in Algorithm 1. Firstly, the dual decomposition method is used to solve the spectrum resource allocation algorithm. The system first allocates spectrum resources for the slice users according to the subproblem (15). Based on the result of spectrum resources allocation, the users determine which RRH can get the maximum transmission rate, then update a_{k,u_n}. Next, update the dual variable according to (17) to (19). Then, CVX is used to slove the computing resource allocation problem. Finally, the resource utilization is calculated. This iterates over and over until you find the optimal value for resource utilization.

4 Simulation Results

In this section, the performance of the proposed scheme is evaluated by simulations. In addition to the proposed scheme, we also introduced the other two resource allocation scheme for reference, including the joint resource allocation scheme of network slice under D-RAN and the static resource allocation scheme of network slice under C-RAN. For convenience, scheme 1 refer to the scheme proposed in this paper, scheme 2 refer to the joint resource allocation scheme of network slice under D-RAN, and scheme 3 refer to the static resource allocation

Algorithm 1. Joint Resource Allocation Algorithm based on Network Slice

Fix step sizes ρ_1, ρ_2 and ρ_3; Initialize dual variables α, β_k and η_{k,u_n}; Set $a_{k,u_n} = 1$ and the number of iterations t=1;

for t **do**

    According to subproblem (15), the spectrum resource allocation b_{k,u_n} is determined;

    According to the spectrum allocation, the user updates a_{k,u_n}according to the formula (16);

    Update the dual variables α, $\beta_k$and γ_{k,u_n} according to formulas (17) to (19);

    According to the result of spectrum resource allocation problem, CVX is used to solve c_{k,u_n};

    Calculate resource utilization η according to the formula (8);

    if Resource utilization convergence **then**
        Break
    else
        t=t+1
    end

end

scheme of network slice under C-RAN. In scheme 2, the spectrum resources and computing resources in the communication system belong to each base station respectively, and the resources between base stations cannot be shared. After the user establishes the connection with the base station, the allocation of computing resources and spectrum resources is determined by the base station. In scheme 3, the allocation of spectrum resources and computing resources is not dynamic, but static segmentation according to the communication requirements of slices.

In the simulation, we consider a C-RAN system, in which the total spectrum resource is 50 Mhz and the computational resource is 50 MIPS. We apply the MATLAB simulation tool for simulation. In this system, there are 4 RRH, the distance between each RRH is 500 m, and the transmission power of RRH is 54 W. In order to calculate the SINR, we need to know the channel condition information and the thermal noise density. Therefore, we set $\sigma^2 = -174$ dBm. What's more, following paper [4], we set the pass loss model to $36.7log(dist) + 22.7 + 26log(f_c)$, where $dist$ refer to the distant between the user and RRH and $f_c = 2.5$ Ghz. In addition, there are three types of slices and several users in the system. The minimum transmission rate of users under each slice is 0.128 Mbit/s, 1 Mbit/s and 10 Mbit/s, and the users are randomly distributed in the system.

When the transmission power of RRH is constantly increasing, the change of resource utilization of the system is shown in Fig. 2, where it is assumed that there are 15 users in the system. It can be seen that with the increase of transmission power RRH, the resource utilization of scheme 1 is the highest. And the resources utilization rate of scheme 2 is the lowest. This is because the computing resources and spectrum resources in scheme 1 and scheme 3 are shared, while the computing resources and spectrum resources in scheme 2 are owned by each base station. And the resources between base stations are not shared, therefore cause the low resource utilization.

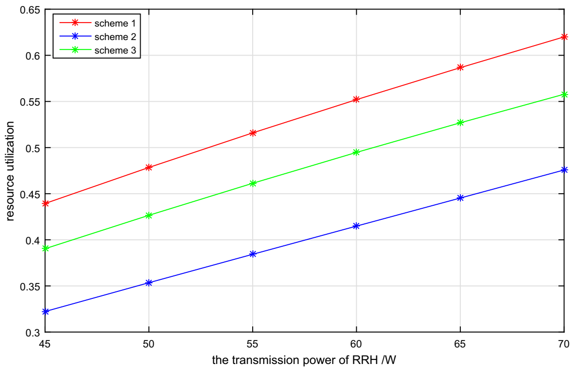

Fig. 2. The change of resource utilization in the system with the increase of RRH transmission power

When the number of users in the simulation increases, the variation of the system's resource utilization is shown in Fig. 3. As can be seen from the Fig. 3, when the number of users in the simulation are increasing, the resource utilization rate of scheme 1 is the highest, and the resource utilization rate of scheme 2 is the lowest. However, in the process of increasing the number of users, the resource utilization of scheme 2 keeps rising and the resource utilization of scheme 3 keeps falling. Moreover, when the number of users in the system reaches 30, the resource utilization of scheme 2 has exceeded scheme 3.

To further explore the performance of the three schemes, we analyzed the number of users that the three schemes could serve when the number of users in the system are increasing, as shown in Fig. 4. As can be seen from Fig. 4, scheme 1 can serve the largest number of users, while scheme 3 can serve the least number of users. According to Fig. 3 and Fig. 4, scheme 1 has the best performance. This is because the resources in scheme 1 are shared together and allocated according to users' requirement, so the resource utilization can be higher and the number of users can be served is larger. However, comparing with scheme 1, scheme 3 is a static resource allocation scheme. The static resource allocation scheme will result in insufficient liquidity of resources, which leads to the resource utilization of scheme 3 is not higher than scheme 1. Comparing with sheme 1, the resources of scheme 2 are owned by each base station, and the resources among base stations cannot be shared, which will definitely lead to the waste of resource. Thus, the resource utilization of scheme 2 is not higher than scheme 1. But, compared with scheme 3, scheme 2 is a dynamic resource allocation scheme. The resource allocation of scheme 2 can be changed according to the number of users so as to increase the number of users it can serve. Moreover, when the number of users in the system is large, the resource utilization of scheme 2 will be higher than scheme 3.

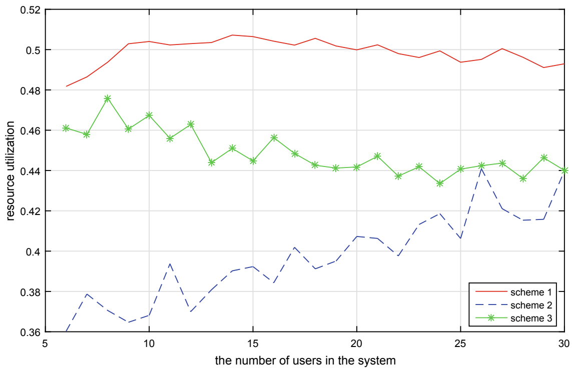

Fig. 3. The change of resource utilization in a system as the number of users increases

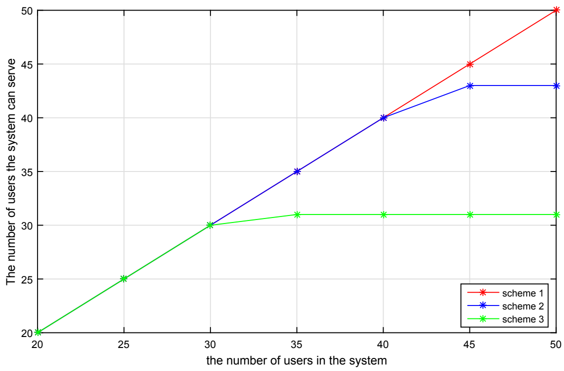

Fig. 4. The number of users that can be served in a system as the number of users increases

5 Conclusion

In this paper, a joint resource allocation scheme based on network slices is proposed under the C-RAN network architecture. This scheme not only solves the problem of joint allocation of spectrum resources and computing resources in the system, but also considers the limitation of transmission rate between RRH and fronthaul link. We models the joint resource allocation problem as a MINLP problem. According to the property of the problem, the joint resource allocation problem of network slicing is decomposed into two sub-problems for solving respectively. In order to verify the effectiveness of the model, we introduced the other two scheme to compare. Numerical simulation shows that the proposed scheme has better resource utilization than the other two schemes and can serves more users.

References

1. Boyd, S., Grant, M.: CVX users' guide (2011). http://cvxr.com/cvx/doc/
2. Costanzo, S., Fajjari, I., Aitsaadi, N., Langar, R.: DEMO: SDN-based network slicing in C-RAN. In: 2018 15th IEEE Annual Consumer Communications Networking Conference (CCNC), pp. 1–2 (2018)
3. De Domenico, A., Liu, Y., Yu, W.: Optimal computational resource allocation and network slicing deployment in 5G hybrid C-RAN. In: 2019 IEEE International Conference on Communications (ICC), ICC 2019, pp. 1–6 (2019)
4. Jian, Z., Muqing, W., Ruiqiang, M., Xiusheng, W.: Dynamic resource sharing scheme across network slicing for multi-tenant C-RANs. In: 2018 IEEE/CIC International Conference on Communications in China (ICCC Workshops), pp. 172–177 (2018)
5. Li, X., et al.: Network slicing for 5G: challenges and opportunities. IEEE Internet Comput. **21**(5), 20–27 (2017)

6. Li, Y., Xia, H., Wu, S., Lu, C.: Joint optimization of computing and radio resource under outage QoS constraint in C-RAN. In: 2017 International Symposium on Wireless Communication Systems (ISWCS), pp. 107–111 (2017)
7. Liu, J., Zhou, S., Gong, J., Niu, Z., Xu, S.: Statistical multiplexing gain analysis of heterogeneous virtual base station pools in cloud radio access networks. IEEE Trans. Wirel. Commun. **15**(8), 5681–5694 (2016)
8. Liu, Q., Han, T., Wu, G.: Computing resource aware energy saving scheme for cloud radio access networks. In: 2016 IEEE International Conferences on Big Data and Cloud Computing (BDCloud), Social Computing and Networking (SocialCom), Sustainable Computing and Communications (SustainCom) (BDCloud-SocialCom-SustainCom), pp. 541–547 (2016)
9. Pompili, D., Hajisami, A., Tran, T.X.: Elastic resource utilization framework for high capacity and energy efficiency in cloud ran. IEEE Commun. Mag. **54**(1), 26–32 (2016)
10. Tang, J., Shim, B., Quek, T.Q.S.: Service multiplexing and revenue maximization in sliced C-RAN incorporated with URLLC and multicast EMBB. IEEE J. Sel. Areas Commun. **37**(4), 881–895 (2019)
11. Tran, T.X., Pompili, D.: Dynamic radio cooperation for user-centric cloud-ran with computing resource sharing. IEEE Trans. Wirel. Commun. **16**(4), 2379–2393 (2017)
12. Yu, W., Lui, R.: Dual methods for nonconvex spectrum optimization of multicarrier systems. IEEE Trans. Commun. **54**(7), 1310–1322 (2006)
13. Ye, Q., Rong, B., Chen, Y., Al-Shalash, M., Caramanis, C., Andrews, J.G.: User association for load balancing in heterogeneous cellular networks. IEEE Trans. Wirel. Commun. **12**(6), 2706–2716 (2013)
14. Zhang, H., Wong, V.W.S.: A two-timescale approach for network slicing in C-RAN. IEEE Trans. Veh. Technol. **69**(6), 6656–6669 (2020)