Joint User-Association and Resource-Allocation in Virtualized C-RAN

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Abstract. The Cloud Radio Access Network (C-RAN), which is a novel architecture, has been proposed as a promising solution to overcome the challenges of Next Generation (5G) cellular networks, in terms of efficiency, capacity, scalability, flexibility and sustainability in a cost-effective way. In this paper, we develop an efficient resource allocation scheme in the fronthaul-constrained C-RAN to support users of different slices (service providers). Multiple slices (service providers) share the resource of an InP, each slice has its own quality-of-service (QoS) requirement. In specific, we formulate an optimization problem for maximizing network throughput by joint subcarrier, power allocation and user-RRH association assignment in the downlink transmission of C-RAN. This problem is NP-hard, therefore, we introduce a two-step suboptimal algorithm to solve it. The original problem is decomposed into joint power and subcarrier allocation subproblem and user-RRH association assignment subproblem. Firstly, we solving the user-RRH association subproblem under the fronthaul capacity constraint by the binary search algorithm. Then the dual decomposition algorithm is used to solve the power and subcarrier allocation subproblem. Simulation results demonstrate the effectiveness of our proposed algorithm.

Keywords: Virtualized C-RAN · Fronthaul constrained
Joint subcarrier · Power and user-RRH association assignment

1 Introduction

Cloud radio access network (C-RAN) is a promising and cost-efficient mobile network architecture, which can improve network capacity and coverage to handle the ever-growing demand for mobile data transmission in 5G network [1]. The basic concept of C-RAN is to decouple traditional base station (BS) functions into two parts: the distributed installed remote radio heads (RRHs) and the baseband units (BBUs) clustered as a BBU pool in a centralized cloud server. As presented in the Fig. 1, a mobile user can be associated with one or multiple RRHs through wireless channel, and RRHs are connected to the BBU pool via the high-speed, low latency fiber transport link (fronthaul) [2,3]. Regardless of reducing the capital expenses (CAPEX) and operational expenses (OPEX)

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that is achieved by C-RAN, a practical fronthaul is always capacity constrained, which will reduce C-RAN performance gain [4].

In C-RAN, supporting for resource sharing among multiple network slices is an important scenario. Network slicing consists of deploying multiple end-to-end logical networks in support of independent business operations. In contrast to deploying an independent network infrastructure, each slice should be possible to realize as a logical network corresponding to a shared infrastructure, which allows serving diverse service requirements and satisfy the traffic growing demand in 5G network [5,6]. For example, the radio resources of a network operator are shared among multiple service providers, which can serve their own users and can be considered as slices [7,8]. Each slice requires a minimum reserved rate representing its QoS requirement.

Resource management always has a significant impact on network performance. To achieve efficient network resource utilization, a network operator requires to dynamically allocate radio resources among service providers (slices). Previous studies have been performed on resource sharing in cellular networks. For example, in [8], a resource management scheme for jointing physical resource block (PRB) and power allocation in LTE system is studied, which schedules the slices based on a proportional fairness rule with the objective to maximize the sum rate. In [9], a resource virtualization scheme is studied by introducing two different types of slices, including rate based and resource-based slices, where the minimum rate and minimum network resources are preserved for each slice, respectively. Generally, these works have focused on analyzing resource virtualization in a single base station, which can't be directly extended to a C-RAN with densely deployed RRHs [10]. An efficient resource sharing mechanism to support multiple slices in a C-RAN can improve network performance and resource utilization efficiency. Therefore, we propose to study the combination of wireless resource virtualization and C-RAN to achieve efficient resource sharing.

Note that without the fronthaul capacity constraint, each user can be served by all RRHs, however, considering the practical fronthaul links are capacity constrained, it is beneficial to optimize the user-RRH association to improve the system performance in C-RAN [11]. Therefore, the main objective of this paper is to propose a new model that a number of slices share the C-RAN. Specifically, we aim to maximize the network throughput by joint optimizing the power, subcarrier allocation and user-RRH association assignment for different slices' users of C-RAN.

It is obvious that the optimization problem is NP-hard, in other words, it can't be optimally solved with large number of users and RRHs in C-RAN. Therefore, we introduce a two-step suboptimal algorithm to practically solve this problem, the optimization problem is decomposed into user-RRH association assignment subproblem and joint power and subcarrier allocation subproblem; the first subproblem can be solved by the binary search algorithm and the second one can be solved by the dual decomposition algorithm. This algorithm is proved to be effective by the simulation results.

The rest of the paper is organized as follows. Section 2 describes the system model and formalizes the problem. Section 3 proposes an algorithm for dynamic resource sharing of all slices' users. In Sect. 4, simulation results demonstrate that the algorithm is effective. Finally, this paper is concluded in Sect. 5.

2 System Model and Problem Formulation

2.1 System Model

As is shown in Fig. 1, we consider the downlink transmission of fronthaul-constrained C-RAN, where the coverage of a specific area is provided by N RRHs. It is assumed that each RRH n is connected to the BBU pool via a fronthaul link with a capacity of T_n. The total system bandwidth of B MHz is divided into C subcarriers and shared by users through orthogonal frequency-division multiple access (OFDMA). The bandwidth of each subcarrier i.e., $\mathcal{B}_c = B/C$ is assumed to be smaller compared to the coherent bandwidth of the wireless channel. Therefore the channel gain of user in each sub-carrier can be considered flat. The system serves a set of slices, $\mathcal{M} = \{1, \cdots, m, \cdots, M\}$, where the slice m has a set of users denoted by $\mathcal{K}_m = \{1, \cdots, k_m, \cdots, K_m\}$ and requests for a minimum reserved rate of R_m^{rsv} to guarantee a minimum acceptable service level for its users. Then the total number of users is $K = \sum_{m=1}^{M} K_m$.

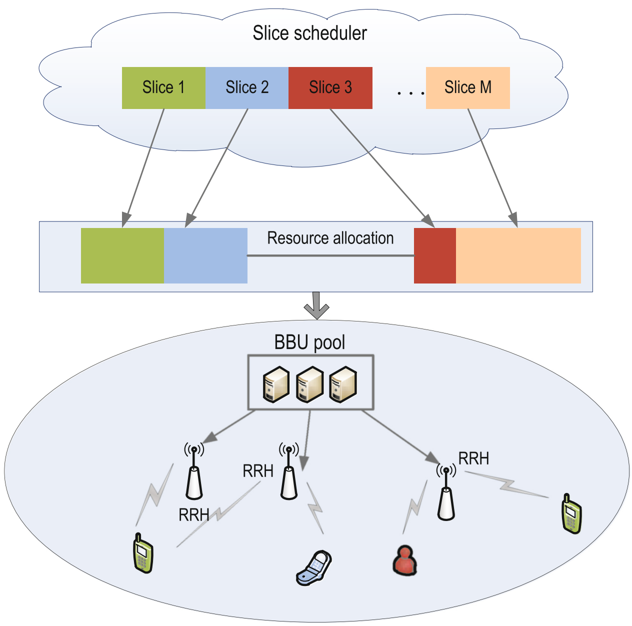

Fig. 1. System model of the downlink communication in C-RAN

Let p_{c,k_m} denotes the allocated power to user k_m on the subcarrier c, and h_{n,c,k_m} is the channel power gain of the wireless link between RRH n and user k_m of slice m over the subcarrier c, which represents the channel state information (CSI). The binary variables α_{c,k_m} and β_{n,k_m} represent the assignment of subcarrier and user-RRH association of user k_m, respectively, and where

$$\alpha_{c,k_m} = \begin{cases} 1 & \text{if subcarrier } c \text{ is allocated to user } k_m \\ 0 & \text{otherwise} \end{cases},$$

$$\beta_{n,k_m} = \begin{cases} 1 & \text{if RRH } n \text{ serves user } k_m \\ 0 & \text{otherwise} \end{cases}.$$

Due to the OFDMA limitation, one subcarrier must be allocated to exactly one user, it is required that $\sum_{m=1}^{M} \sum_{k=1}^{K_m} \alpha_{c,k_m}{=}1$.

2.2 Optimization Problem Formulation

In the downlink of C-RAN, each user has a set of RRHs to provide service, the BBU pool sends the user messages to each serving RRH via its fronthaul link, then each serving RRH upconverts the user messages into wireless signals and sends them to the user [13]. Then the received equivalent baseband transmit signal of user k_m at subcarrier c can be expressed as

$$y_{c,k_m} = \sum_{n \in \mathcal{N}} \beta_{n,k_m} h_{n,c,k_m} w_{n,c,k_m} p_{c,k_m} x_{c,k_m} + z_{c,k_m} \tag{1}$$

where $x_{c,k_m} \sim CN(0,1)$ denotes the transmit message intended for user k_m (which is modeled as a circularly symmetric complex Gaussian (CSCG) random variable with zero-mean and unit-variance), and w_{n,c,k_m} denotes RRH n's normalized precoding vector for user k_m at subcarrier c. $z_{c,k_m} \sim CN(0,\sigma^2)$ is the additive white Gaussian noise (AWGN) at user k_m over subcarrier c, σ^2 is the noise power. Without loss of generality, consider σ^2 to be the same for users in all RRHs and subcarriers. In this paper, it is assumed that BBU pool knows the channels to all the K users perfectly.

According to formulation (1), the decoding SNR for user k_m at subcarrier c is thus expressed as

$$r_{c,k_m} = \frac{\sum_{n \in \mathcal{N}} \beta_{n,k_m} \left| h_{n,c,k_m} \right|^2 p_{c,k_m}}{\sigma^2} \qquad \forall c, k \tag{2}$$

Then, the achievable rate of user k_m at subcarrier c in Mbps is given by

$$\begin{aligned} R_{c,k_m} &= B_c \log_2(1 + r_{c,k_m}) \\ &= B_c \log_2(1 + \frac{\sum_{n \in \mathcal{N}} \beta_{n,k_m} \left| h_{n,c,k_m} \right|^2 p_{c,k_m}}{\sigma^2}) \end{aligned} \tag{3}$$

Considering that all users served by RRH n share its maximum transmit power P_n, then the power constraint can be formulated as:

$$C1: \sum_{m \in \mathcal{M}} \sum_{k \in \mathcal{K}_m} \sum_{c \in \mathcal{C}} \alpha_{c,k_m} \beta_{n,k_m} P_{c,k_m} \le P_n \qquad \forall n \tag{4}$$

If user k_m is served by RRH n, BBU pool will send the digital messages for user k_m to RRH n over its fronthaul link n at a rate of $R_{k_m,n}$, which is the transmitted rate of user k_m in all allocated subcarriers from RRH n. Therefore, take the fronthaul capacity constraint of RRH n into account, it can be expressed as :

$$C2: \quad \sum_{m\in\mathcal{M}}\sum_{k\in\mathcal{K}_m}\sum_{c\in\mathcal{C}}\alpha_{c,k_m}\beta_{n,k_m}R_{c,k_m} \leq T_n \qquad \forall n \tag{5}$$

The required minimum reserve rate of slice m to guarantee its QoS requirement can be represented as:

$$C3: \quad \sum_{k\in\mathcal{K}_m}\sum_{c\in\mathcal{C}}\alpha_{c,k_m}R_{c,k_m} \geq R_m^{rsv} \qquad \forall m \tag{6}$$

Next, the constraint of OFDMA in subcarriers allocation can be given below:

$$C4: \quad \sum_{m\in\mathcal{M}}\sum_{k\in\mathcal{K}_m}\alpha_{c,k_m} \leq 1 \qquad \forall c \tag{7}$$

Hence, in order to achieve maximum network throughput of users of all slices, the joint power, subcarrier and RRH assignment for different slices' users in this system can be formulated as:

$$\begin{aligned} &\max_{\{\boldsymbol{p},\boldsymbol{\alpha},\boldsymbol{\beta}\}} \textstyle\sum_{m\in\mathcal{M}}\sum_{k\in\mathcal{K}_m}\sum_{c\in\mathcal{C}}\alpha_{c,k_m}R_{c,k_m} \\ &\quad subject\,to: \quad C1,\, C2,\, C3 \; and \; C4 \end{aligned} \tag{8}$$

3 Joint User-RRH Association and Resource Allocation

The optimization problem (8) is a non-convex mixed-integer problem, which has one continuous variable $\boldsymbol{p}$ and two binary variables $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$. Such an optimization problem is always NP hard [15], therefore, we propose an efficient two-step algorithm that is based on the decomposition of the original problem to the separate tasks of RRH assignment and joint subcarrier and power allocation, which obtains a suboptimal solution in general [14].

3.1 User-RRH Association Optimization Problem

Due to the fronthaul capacity is constrained, a user can't be served by all the RRHs, hence, we make attempt to optimize the user-RRH association for slices' users in C-RAN in problem (8). However, it is difficult to solve. In order to simplify the original problem (8), we separate the user-RRH association (fronthaul link) assignment problem from it, then propose a binary search method to allocate the fronthaul link by optimization maximizing the total rate gain over the active fronthaul links. Given the assumptions that average power distribution p_{k_m} and h_{n,k_m} is the path gain on link RRH n to user k_m without channel variations, the rate of user k_m transmitted by RRH n is

$$R_{n,k_m} = B\log 2(1+\frac{|h_{n,k_m}|^2\,p_{k_m}}{\sigma^2}) \tag{9}$$

Therefore, this optimization subproblem can be derived as :

$$\begin{aligned} \max_{\{\beta\}} & \sum_{m\in\mathcal{M}}\sum_{k\in\mathcal{K}_m}\sum_{n\in\mathcal{N}}\beta_{n,k_m}R_{n,k_m} \\ s.t. \quad & \sum_{n\in\mathcal{N}}\beta_{n,k_m}\le S \qquad \forall k \\ & \sum_{m\in\mathcal{M}}\sum_{k\in\mathcal{K}_m}\beta_{n,k_m}R_{n,k_m}\le T_n \qquad \forall n \end{aligned} \tag{10}$$

where the first constraint in problem (10) ensures each user can be connected with no more than s RRHs, so that to facilitate the simple binary search method to solve the allocation of fronthaul link. While the second constraint ensures that the sum-rate of users served by RRH n satisfies the capacity limitation of fronthaul link n. Then the fronthaul link allocation optimization problem can be solved by the binary search algorithm, it can be shown:

Algorithm 1. Binary-search algorithm

Initialization: $\boldsymbol{R_{n,k_m}} = \{R_{n,k_m}\} \in \mathbb{R}^{N\times K}$
user-RRH association set: $\boldsymbol{\beta} \leftarrow \mathbf{0} \in \mathbb{R}^{N\times K}$
for $n = 1, 2, ..., N$
Initialize $R_n = 0$
Repeat
  for $k = 1, 2, ...k_m, ..., K$
  Find the user-RRH association:
    $(k_m^*, n^*) = \text{argmax}(R_{n,k_m})$
    if $R_n + R_{n^*,k_m^*} \le T_n$ and $\sum_{n\in\mathcal{N}}\beta_{n,k_m} < S$
    then: $R_n \leftarrow R_n + R_{n^*,k_m^*}$
    $\beta(n^*, k_m^*) \leftarrow 1$
    $\boldsymbol{R_{n,k_m}} \leftarrow \boldsymbol{R_{n,k_m}} - \{R_{n^*,k_m^*}\}$
    end if
  end for
end for
Output $\boldsymbol{\beta}$
Solve optimization problem (10).

3.2 Joint Subcarrier and Power Allocation Scheme

Given a feasible user-RRH association assignment, the value of $\boldsymbol{\beta}$ is determined, then the optimization problem of joint subcarrier and power allocation on different fronthaul links can be separated from problem (8) and expressed as:

$$\begin{aligned} \max_{\{\boldsymbol{p},\alpha\}} & \sum_{m\in\mathcal{M}}\sum_{k\in\mathcal{K}_m}\sum_{c\in\mathcal{C}}\alpha_{c,k_m}R_{c,k_m} \\ s.t. \quad & constraints \quad C1, C3, C4 \end{aligned} \tag{11}$$

The problem (11) is still a mixed binary integer nonlinear programming problem, the decision variables α and p in the problem are binary variables and continuous variables, respectively. Such an optimization problem is generally hard to solve. Then the dual decomposition algorithm can be used to solve the problem effectively [15], since the duality gap between the primal problem and the dual problem in a multicarrier system is approximately zero for a large number of subcarriers [16].

First, we obtain the Lagrangian function of the original problem (11) as follows:

$$\begin{aligned} &L(\boldsymbol{p},\boldsymbol{\alpha},\boldsymbol{\lambda},\boldsymbol{\eta}) \\ &= \sum_{m\in\mathcal{M}}\sum_{k\in\mathcal{K}_m}\sum_{c\in\mathcal{C}}\alpha_{c,k_m}R_{c,k_m} \\ &- \sum_{n\in\mathcal{N}}\lambda_n(\sum_{m\in\mathcal{M}}\sum_{k\in\mathcal{K}_m}\sum_{c\in\mathcal{C}}\alpha_{c,k_m}\beta_{n,k_m}p_{c,k_m} - P_n) \\ &+ \sum_{m\in\mathcal{M}}\eta_m(\sum_{k\in\mathcal{K}_m}\sum_{c\in\mathcal{C}}\alpha_{c,k_m}R_{c,k_m} - R_m^{rsv}) \end{aligned} \tag{12}$$

where $\boldsymbol{\lambda} = [\lambda_1, \lambda_2, ..., \lambda_N]^T, \boldsymbol{\eta} = [\eta_1, \eta_2, ..., \eta_M]^T$ are dual variables. Thus, we can get the dual objective function of the original problem expressed as:

$$g(\boldsymbol{\lambda},\boldsymbol{\eta}) = \max_{\{\boldsymbol{p},\boldsymbol{\alpha}\}} L(\boldsymbol{p},\boldsymbol{\alpha},\boldsymbol{\lambda},\boldsymbol{\eta}) \tag{13}$$

The dual problem of the original problem (11) can be expressed as follows:

$$\begin{aligned} &\min_{\{\boldsymbol{\lambda},\boldsymbol{\eta}\}} \quad g(\boldsymbol{\lambda},\boldsymbol{\eta}) \\ &s.t. \quad \boldsymbol{\lambda} \geq \mathbf{0}, \boldsymbol{\eta} \geq \mathbf{0} \end{aligned} \tag{14}$$

Then the original problem is divided into one main problem and $C \times K$ subproblems by dual decomposition.

When the Lagrange multipliers are determined, $\sum_{n\in\mathcal{N}}\lambda_n P_n$ and $\sum_{m\in\mathcal{M}}\eta_m R_m^{rsv}$ are constants. For given $\boldsymbol{\alpha}$, we can first derive the optimal power allocation $\boldsymbol{P^*}$ from the subproblem below:

$$\begin{aligned} &\max_{\{\boldsymbol{p}\}} \quad (1+\eta_m)R_{c,k_m} - \sum\nolimits_{n\in\mathcal{N}}\lambda_n\beta_{n,k_m}p_{c,k_m} \\ &\qquad s.t. \quad p_{c,k_m} \geq 0 \quad \forall c, k \end{aligned} \tag{15}$$

Based on the optimal power allocation $\boldsymbol{P^*}$, we can obtain the rate set $\{R_{c,1}, ..., R_{c,K}\}$ of subcarrier c, therefore, the subcarriers $\boldsymbol{\alpha^*}$ are allocated according to the rule:

$$\alpha_{c,k_m^*} = \begin{cases} 1 & k_m^* = \arg\max_{\{\boldsymbol{k}\}} R_{c,k_m} \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

In other word, the idea of this rule is to allocate subcarriers to users that have high performance gains. After solving above subcarrier assignment problems and $C \times K$ subproblems, the dual objective function $g(\boldsymbol{\lambda},\boldsymbol{\eta})$ can be obtained.

With the help of sub-gradient method, the dual problem (14) to find the optimal values of dual variables can be solved. Based on the obtained power value P^*, subcarrier allocation value α^*_{c,k_m}, user-RRH association β_{n,k_m} and the initial $\boldsymbol{\lambda}_0$, $\boldsymbol{\eta}_0$, the dual variables at the $(t+1)$-th iteration can be updated as:

$$\begin{aligned} \lambda_n^{(t+1)} &= \Big[\lambda_n^{(t)} - \delta_1^{(t)}(P_n - \sum_{k\in\mathcal{K}}\sum_{c\in\mathcal{C}} \alpha^*_{c,k_m}\beta^*_{n,k_m}P_{c,k_m})\Big]^+ \\ \eta_m^{(t+1)} &= \Big[\eta_m^{(t)} - \delta_2^{(t)}(\sum_{k\in\mathcal{K}_m}\sum_{c\in\mathcal{C}} \alpha^*_{c,k_m}R_{c,k_m} - R_m^{rsv})\Big]^+ \end{aligned} \tag{17}$$

where $[x]^+ = \max\{0, x\}$, $\delta_1^{(t)}$ and $\delta_2^{(t)}$ are appropriate step size of the t-th iteration to guarantee the convergence of the sub-gradient method. In order to solve the problem (11), the allocated power P^* and subcarrier α^* should be recomputed under $\lambda(t)$ and $\eta(t)$. Once converged, the iteration will be stopped. Then the original optimization problem (8) for jointing power, subcarrier, and user-RRH association assignment for different slices' users in C-RAN can be solved.

3.3 Comparison Schemes

Besides two-step Algorithm 1 proposed above, we also consider the following benchmark schemes for network performance comparison.

◦ Benchmark Scheme 1: Static resource sharing for different Slices (Algorithm 2). According to the service level agreement (SLA) between slices, different slices in system statically share radio resources and RRHs by a certain percentage. In this paper, we determine the resources allocation percentage based on the number of users served by different slices. Then each slice dynamically allocates the acquired resource to its users with the goal of maximizing the network throughput.

◦ Benchmark Scheme 2: Average resource allocation algorithm (Algorithm 3). We distribute subcarrier, power and RRH equally to all users of different slices, regardless of the channel characteristics of the different subcarriers and the service level agreement (SLA) between slices.

4 Simulation Results

In this section, simulation results are provided to evaluate the performance of our proposed two-step algorithm for joint power and subcarrier and RRH assignment for users of different slices in C-RAN. Let's consider a virtualized C-RAN scenario with $N = 5$ RRHs serving M = 2 slices (service providers). Without loss of generality, the channels of different subcarriers are assumed to be independent of one another, and taken from i.i.d. complex Gaussian random variables with zero mean and unit variance. Each slice (service providers) serves a number of users. Furthermore, the minimum reserved rate R_m^{rsv} for each slice m is determined according to its QoS requirement. For all of our simulations, we assume

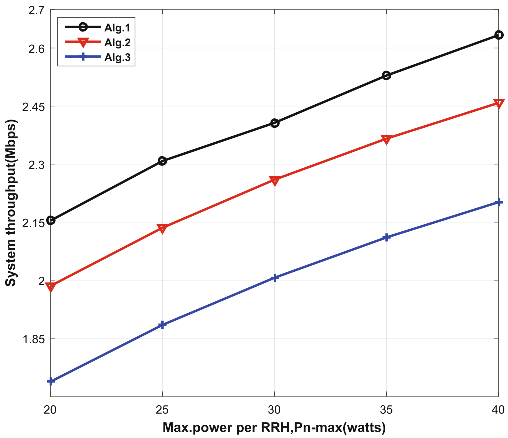

Fig. 2. Total throughput versus maximum transmit power of RRH

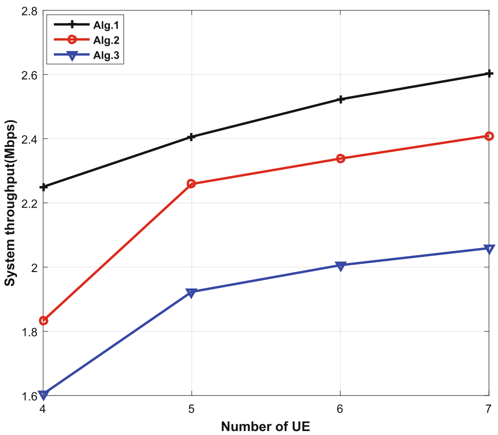

Fig. 3. Total throughput versus number of users, K

the fronthaul capacity T_n and the available power P_n are same for all RRH n, and $T_n = 1$ Mbps, each user could be served by no more than 3 RRHs.

Firstly, we evaluate and compare the total throughput achieved by Algorithm 1, Algorithm 2 and Algorithm 3 versus the maximum transmit power P_n and the number of users K in Figs. 2 and 3, respectively. Part of simulation parameters can be set to: in Fig. 2, $K = 5$, slice 1 has 3 users and the minimum reserved rate $R_1^{rsv} = 1$ Mbps, while slice 2 has 2 users and $R_2^{rsv} = 0.6$ Mbps. In Fig. 3, we evaluate the total throughput achieved for different number of users when $P_n = 30$ watts. The results in both Figs. 2 and 3 indicate that Algorithm 1 considerably outperforms Algorithm 2 and Algorithm 3 for different values of P_n and K.

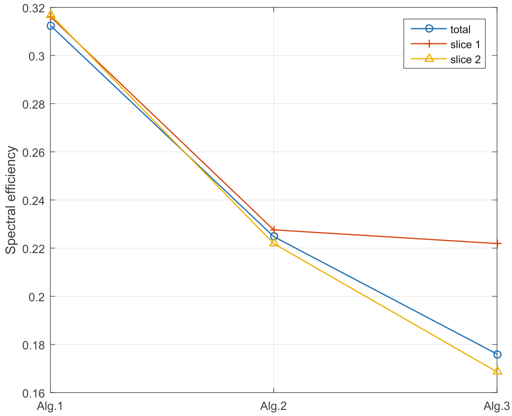

Fig. 4. Spectral efficiency

Then we evaluate and compare the spectral efficiency achieved by Algorithm 1, Algorithm 2 and Algorithm 3 for slice 1, slice 2 and the whole network. Where each slice has 3 users with the $P_n = 30$ watts, $R_1^{rsv} = R_2^{rsv} = 1$ Mbps. The results can be shown in Fig. 4 revealing that resource utilization achieved by Algorithm 1 is higher than Algorithm 2 and Algorithm 3. The resource allocation scheme based on Algorithm 1 and Algorithm 2 both can satisfy the SLA constraint between different slices, however, each slice assigns resources to its own users independently in Algorithm 2, hence, it can't achieve the dynamic sharing of resources between different slices. For Algorithm 3, lacking of flexibility in resource allocation leads to low resource utilization and can't achieve on-demand resources allocation for different slices.

5 Conclusion

In this paper, we considered a set of slices (service providers) in C-RAN, each of which serves its own users and requires a minimum reserved rate, then we formulate an NP-hard problem for jointing subcarrier and power allocation and RRH assignment for different slices' users. In order to solve it effectively, a two-step suboptimization algorithm is proposed. Numerical results confirm that the proposed algorithm is more efficient than other approaches. Furthermore, they show the algorithm can satisfy the QoS requirement of different slices' users and achieve better network performance in both throughput and spectral efficiency.

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