Joint User Association and RRH Clustering in Cloud Radio Access Networks

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***Abstract*—Cloud Radio Access Network (C-RAN) has emerged as a promising network architecture for 5G cellular networks. The conventional base station is broken down into a Remote Radio Head (RRH) and a Base Band Unit (BBU). The RRHs are geographically scattered across multiple sites, whereas the BBUs are sheltered in a data center. In this context, deciding to which RRH users connect is known as the user association problem. As a function of network load conditions, some RRHs may be turned off, reducing network power consumption. Furthermore, RRHs may be mapped to a single BBU, achieving statistical multiplexing gain. Deciding what RRHs are grouped together is known as the RRH clustering problem. Traditionally, user association and RRH clustering are independently addressed. As these two problems are mutually dependent, we provide in this paper a framework for the joint optimization of the user association and the RRH clustering. Our objective is to minimize both the network power consumption and the total transmission delay. As this problem is a mixed integer non-linear programming problem, it can be solved through exhaustive search. However, the computational complexity becomes intractable as the network size increases. Therefore, we decouple our joint problem into two sub-problems. These sub-problems are iteratively solved until convergence. We further evaluate the performance of our proposed solution. Simulation results show that our optimal solution for the RRH clustering sub-problem outperforms the no-clustering solution, where one BBU is exclusively dedicated to each RRH, and the grand coalition solution, where all RRHs are associated with a single BBU.**

I. Introduction

In recent years, global mobile data traffic has been exponentially increasing [1]. 5G cellular networks are expected to cope with this impressive growth, while minimizing network capital and operating expenditures. In this context, Cloud Radio Access Network (C-RAN) has emerged as a promising network architecture. The conventional base station is broken down into a Remote Radio Head (RRH) and a Base Band Unit (BBU). The RRHs are geographically scattered across multiple sites, whereas the BBUs are sheltered in a cloud data center. Moreover, the RRHs are connected to the BBUs through high-performance optical fronthaul links.

To cope with the huge demand for capacity, RRHs need to be densely deployed. In this context, deciding to which RRH users connect is known as the user association problem. Ideally, user association decisions depend on radio resource availabilities and user radio conditions. For instance, a user will preferably connect to a RRH whose radio signals are well received and who can provide acceptable quality of service. Moreover, as a function of network load conditions, inefficient RRHs – with no associated users – can be turned off. This reduces the network power consumption. Furthermore, RRHs may be mapped to a single BBU, achieving statistical multiplexing gain. For example, RRHs to which few users are connected can be associated with only one BBU, sharing the same radio resource pool. This further reduces the network power consumption and the total interference level. Deciding what RRHs are grouped together is known as the RRH clustering problem.

In the literature, user association and RRH clustering have been largely addressed independently. However, in practice, these two problems are mutually dependent. On the one hand, user association decisions depend on radio resource availabilities and user radio conditions. Both depend on the RRH clusters that have been formed. For instance, when RRHs to which many users are connected have been associated with a single BBU, new arrivals avoid joining these RRHs. If they do, their connected users receive low average rates. Besides, neighboring RRHs that have been mapped to only one BBU suffer from relatively low interferences. In fact, the intra-cluster interference is eliminated as only one user per BBU is served at a time. Users, that are connected to these RRHs, will have very favorable radio conditions. On the other hand, RRH clustering depends on RRH load conditions and consequently on user association decisions. Clustering decisions are ideally load-aware, so as to minimize the number of active BBUs while providing acceptable quality of service.

In this paper, we tackle the joint user association and RRH clustering problem. Our objective is to minimize both the network power consumption and the total transmission delay. The latter reflects users quality of service and is defined as the sum of data unit transmission delays of all users in the network. As this problem is a mixed integer non-linear programming problem, it can be solved through exhaustive search. However, the computational complexity becomes intractable as the network size increases. Therefore, we decouple our joint problem into two sub-problems: the user association (UA) sub-problem and the RRH clustering (RC) sub-problem. These sub-problems are iteratively solved until convergence, or in other terms until no more user-RRH associations and RRH clustering are to be further modified.

II. Related Work

User association and RRH clustering need to be carefully tackled to improve network performances and reduce network power consumption. In the literature, the two problems have been largely addressed independently. The works in [2], [3] have focused on the user association problem. In [2], the authors propose an energy efficient user association scheme, where the objective is to minimize the power consumption of the fronthaul links. Besides, three heuristic user association algorithms have been developed to allow underutilized RRH to be switched off. The authors in [3] suggest a coordinated scheduling algorithm for the downlink in C-RAN. Under fixed power transmission, the adaptive user association is formulated as a discrete combinatorial optimization problem that aims to maximize the overall network utilization, expressed as the sum of user rates. Given the problem complexity, the authors introduce an interference-aware greedy heuristic solution. Furthermore, the works in [4], [5] and [6] have tackled the RRH clustering problem. In [4], RRH clustering was portrayed as a coalition formation game, where the objective is to optimize network rate, power consumption, and handover frequency. In [5], the authors formulate the BBU-RRH mapping as a modified bin packing problem that aims to minimize the number of used BBUs, in order to enhance radio resource utilization and reduce power consumption. The authors in [6] formulate the RRH clustering problem as a Set Partitioning Problem, considering inter-cluster interferences. The objective is to minimize network power consumption, while guaranteeing minimum rate requirements. Moreover, few articles have jointly addressed the user association and RRH clustering problems. The authors in [7] present one of the works addressing the dependency between the two problems. They propose a dynamic two-stage design. First stage, Branch & Cut algorithm is used to find the proper user-RRH association. Second stage, BBU-RRH clustering is modeled as a Multiple Knapsack Problem, and is based on the output of the first stage. However, inter-cluster interferences are ignored, which have a serious impact on network performances as demonstrated in [6]. To reduce the energy consumption, the authors in [8] propose an energy-saving algorithm with joint user association and clustering strategies. First, to solve the user association sub-problem, an optimal association policy is applied, based on load balancing and energy efficiency. Second, the clustering sub-problem is modeled as an integer linear programming, based on the location and load of the base stations. Yet, this study overlooks user quality of service and does not iteratively solve the two sub-problems until reaching a stable and jointly efficient solution.

In this paper, the main contributions can be summarized as follows:

- We formulate the joint user association and RRH clustering problem, taking into account inter-cluster interferences. Our objective is to minimize both the network power consumption and the total transmission delay. The latter reflects users quality of service and is defined as the sum of data unit transmission delays of all users in the network.
- To deal with the high computational complexity of the joint problem, we decouple it into two sub-problems: the user association (UA) sub-problem and the RRH clustering (RC) sub-problem. Further, to find a jointly efficient solution, these sub-problems are iteratively solved until convergence, or in other terms until no more user-RRH associations and RRH clustering need to be further modified. Simulation results show that our iterative approach converges rapidly within few iterations, providing locally optimal solutions.
- The RC sub-problem is solved through exhaustive search. This optimal solution significantly reduces inter-cluster interferences and network power consumption, while providing high quality of service.

The rest of this paper is organized as follows. Section III describes the system model. In section IV, we provide a framework for the joint optimization of user association and RRH clustering. Section V introduces our iterative approach to solve the joint problem. Simulation results are presented in section VI. Section VII concludes the document.

III. System Model

Consider R RRHs denoted by the set $\mathcal{R} = \{i|1 \leq i \leq R\}$ and K BBUs denoted by the set $\mathcal{K} = \{k|1 \leq k \leq K\}$. While the RRHs are distributed across multiple sites, the BBUs are pooled in a cloud data center. H^i and B^k are two binary variables, which are equal to one if RRH i and BBU k are turned on respectively and zero otherwise. We suppose, in this work, that each RRH can be associated with at most one BBU. We further denote by $\mathcal{U} = \{u|1 \leq u \leq U\}$ the set of active users. We assume, in this work, that each user is associated with at most one RRH. User association and RRH clustering variables are defined as follows:

$$x_i^u = \begin{cases} 1 & \text{if user } u \text{ is associated with RRH } i, \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

$$y_{ik} = \begin{cases} 1 & \text{if RRH } i \text{ is attached to BBU } k, \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

Consequently, the SINR perceived by user u when associated with RRH i, that is mapped to BBU k, can be written as:

$$\Gamma_{ik}^u = \frac{P_i G_i^u}{N_0 + \sum_{j \neq i}(1 - y_{jk}) P_j G_j^u}, \tag{3}$$

where P_i is the transmit power of RRH i, G_i^u is the channel gain between user u and RRH i, and N_0 is the thermal noise power. Particularly, $\sum_{j \neq i}(1 - y_{jk}) P_j G_j^u$ represents inter-cluster interferences, caused by the RRHs that are not associated with BBU k.

Moreover, we denote by $\hat{R_{ik}^u}$ the instantaneous peak rate realized by user u when associated with RRH i, that is mapped to BBU k. $\hat{R_{ik}^u}$ is calculated using the Shannon formula as follows:

$$\hat{R_{ik}^u} = W \log_2(1 + \Gamma_{ik}^u), \tag{4}$$

where W is the total system bandwidth.

A. Delay Model

We denote by R_{ik}^u the average rate perceived by user u when associated with RRH i, that is mapped to BBU k. Assuming a fair resource sharing scheduling, R_{ik}^u is expressed as:

$$R_{ik}^u = \frac{\hat{R_{ik}^u}}{\sum_i \sum_u x_i^u y_{ik}}, \tag{5}$$

where $\sum_i \sum_u x_i^u y_{ik}$ represents the number of users belonging to BBU k. Note that R_{ik}^u depends on user u radio conditions as well as on BBU k load.

Besides, we denote by $T_{i,k}^u$ the amount of time RRH i, that is mapped to BBU k, needs to send a data unit to user u. In fact, the delay needed to transmit a bit for a given user is the inverse of the average rate perceived by this user. Therefore, $T_{i,k}^u$ can be written as:

$$T_{i,k}^u = \frac{1}{R_{ik}^u} = \frac{\sum_i \sum_u x_i^u y_{ik}}{\hat{R_{ik}^u}}. \tag{6}$$

B. C-RAN Power Consumption Model

The C-RAN power consumption, denoted by P_{total}, is the sum of the BBUs power consumption and the RRHs power consumption:

$$P_{total} = \sum_{k \in \mathcal{K}} P_{BBU_k} + \sum_{i \in \mathcal{R}} P_{RRH_i}, \tag{7}$$

where P_{BBU_k} and P_{RRH_i} respectively denote the power consumed by BBU k and RRH i.

According to [9], P_{BBU_k} can be expressed as:

$$P_{BBU_k} = \begin{cases} \lambda & \text{if } B^k = 1, \\ 0 & \text{otherwise}, \end{cases} \tag{8}$$

where λ is a positive constant. Besides, P_{RRH_i} can be written as:

$$P_{RRH_i} = \begin{cases} \delta P_i + P^0 & \text{if } H^i = 1, \\ P^s & \text{otherwise}, \end{cases} \tag{9}$$

where δ is the power amplifier efficiency, P_i is the transmit power of RRH i, and P^0 and P^s are the additional power consumed by RRH i independently of P_i in active mode and sleep mode respectively.

IV. Joint User Association and RRH Clustering Problem

A. Network Cost Function

The network cost function, denoted by C, is defined as the weighted sum of the C-RAN power consumption and the total transmission delay. More precisely, the C-RAN power consumption can be rewritten based on equations (7), (8), and (9) as follows:

$$\begin{aligned} P_{total} &= \sum_{k \in \mathcal{K}} B^k \lambda + \sum_{i \in \mathcal{R}} H^i(\delta P_i + P^0) + \sum_{i \in \mathcal{R}} (1 - H^i) P^s \\ &= \sum_{k \in \mathcal{K}} B^k \lambda + \sum_{i \in \mathcal{R}} (\delta P_i + P^0 - P^s) H^i + \sum_{i \in \mathcal{R}} P^s \end{aligned} \tag{10}$$

Furthermore, the total transmission delay, denoted by T_{total}, is defined as the sum of data unit transmission delays of all active users. Thus, T_{total} is expressed based on equations (3), (4), and (6) as follows:

$$\begin{aligned} T_{total} &= \sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{R}} \sum_{u \in \mathcal{U}} x_i^u y_{ik} T_{i,k}^u \\ &= \sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{R}} \sum_{u \in \mathcal{U}} x_i^u y_{ik} \frac{\sum_i \sum_u x_i^u y_{ik}}{\hat{R_{ik}^u}} \\ &= \sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{R}} \sum_{u \in \mathcal{U}} x_i^u y_{ik} \frac{\sum_i \sum_u x_i^u y_{ik}}{W \log_2(1 + \frac{P_i G_i^u}{N_0 + \sum_{j \neq i} (1 - y_{jk}) P_j G_j^u})} \end{aligned} \tag{11}$$

Consequently, the network cost function C can be written as follows:

$$\begin{aligned} C &= \alpha \alpha' P_{total} + \beta \beta' T_{total} \\ &= \alpha \alpha' \left(\lambda \sum_{k \in \mathcal{K}} B^k + \sum_{i \in \mathcal{R}} (\delta P_i + P^0 - P^s) H^i + \sum_{i \in \mathcal{R}} P^s \right) \\ &+ \beta \beta' \sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{R}} \sum_{u \in \mathcal{U}} x_i^u y_{ik} \frac{\sum_i \sum_u x_i^u y_{ik}}{W \log_2(1 + \frac{P_i G_i^u}{N_0 + \sum_{j \neq i} (1 - y_{jk}) P_j G_j^u})}, \end{aligned} \tag{12}$$

where α' and β' are two normalizing constants, and α and β are the weighting factors that tune the tradeoff between the two components of C. Note that α and β $\in [0, 1]$, and $\alpha + \beta = 1$. Particularly, when α increases, more importance is given to power saving. Yet, when β increases, more emphasis is put on the transmission delay cost.

B. Problem Formulation

Our optimization problem ($\mathcal{P}$) consists in finding the optimal user association and RRH clustering decisions, that minimize the network cost C. Therefore, ($\mathcal{P}$) is given by:

$$\underset{x,y}{\text{minimize}} \quad C(x, y) \tag{13}$$

$$\text{subject to} \quad \sum_{i \in \mathcal{R}} x_i^u \leq 1, \ \forall u \in \mathcal{U} \tag{14}$$

$$\sum_{k \in \mathcal{K}} y_{ik} \leq 1, \ \forall i \in \mathcal{R} \tag{15}$$

$$x_i^u \leq H^i, \ \forall (i, u) : i \in \mathcal{R}, u \in \mathcal{U} \tag{16}$$

$$y_{ik} \leq B^k, \ \forall (i, k) : i \in \mathcal{R}, k \in \mathcal{K} \tag{17}$$

$$x_i^u, y_{ik}, H^i, B^k \in \{0, 1\}, \forall u, \forall i, \forall k \tag{18}$$

Constraints (14) ensure that each user can at most be associated with one RRH. Constraints (15) ensure that each RRH can at most be mapped to one BBU. Constraints (16) indicate that a given RRH is turned on only when at least one user is associated with it. Constraints (17) state that a given BBU is activated only when at least one RRH is mapped to it. Finally, constraints (18) indicate that all the decision variables, namely x_i^u, y_{ik}, H^i, and B^k, are binary.

C. Complexity Analysis

Our problem ($\mathcal{P}$) is a mixed integer nonlinear programming problem, that is NP-hard. The optimal solution can be obtained through exhaustive search. However, this requires exploring all possible user-RRH associations in all possible RRH-BBU configurations. The computational

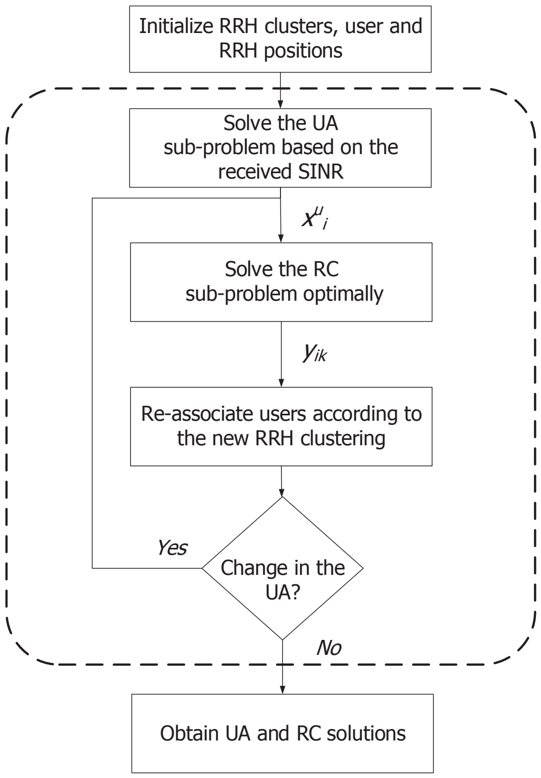

Fig. 1. Iterative approach for the joint user association and RRH clustering problem.

complexity will then be in $O(B_R.R^U)$, where R^U is the number of possible user-RRH associations and B_R is the number of possible RRH-BBU configurations (given by the R-th Bell number). The exhaustive search is consequently extremely computational intensive and becomes prohibitive even for medium-sized networks. To overcome the complexity of the joint problem, we propose in section V an iterative approach that allows reaching stable and jointly efficient solutions.

V. Iterative Approach for the Joint Problem

To overcome the complexity of the joint problem, we present in this section an iterative approach that allows reaching stable and jointly efficient solutions. The idea is to decouple our problem ($\mathcal{P}$) into two sub-problems, namely the user association (UA) sub-problem and the RRH clustering (RC) sub-problem, and to sequentially and iteratively solve them until convergence is achieved. More precisely, assuming an initial RRH clustering, the UA sub-problem is first solved. Then, considering the outputs of the UA sub-problem, the RC sub-problem is solved. Further, depending on the clusters that have been recently formed, user associations may be reconsidered. This is repeated until convergence, or in other terms until no more user-RRH associations and RRH clustering need to be further modified. Thus, the mutual dependence between the UA sub-problem and the RC sub-problem is taken into account, leading to jointly efficient solutions. Fig. 1 illustrates our iterative approach.

A. UA Sub-Problem

Assuming a given RRH clustering (*i.e.,* RRH clustering variables y_{ik} are known), our problem ($\mathcal{P}$) comes down to the following UA sub-problem:

$$\underset{x}{\text{minimize}} \quad C(x) \tag{19}$$

$$\text{subject to} \quad (14) \text{ and } (16) \tag{20}$$

$$x_i^u, H^i \in \{0,1\}, \forall u, \forall i \tag{21}$$

Moreover, P_{total} can be rewritten, by omitting the constant terms in Equation (10), as follows:

$$P_{total} = \sum_{i \in \mathcal{R}} (\delta P_i + P^0 - P^s) H^i \tag{22}$$

Therefore, C can be expressed as:

$$C = \alpha\alpha' \sum_{i \in \mathcal{R}} (\delta P_i + P^0 - P^s) H^i + \beta\beta' \sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{R}} \sum_{u \in \mathcal{U}} x_i^u y_{ik} \frac{\sum_i \sum_u x_i^u y_{ik}}{W \log_2(1 + \frac{P_i G_i^u}{N_0 + \sum_{j \neq i} (1 - y_{jk}) P_j G_j^u})} \tag{23}$$

Since y_{ik} are known, the complexity to find the optimal UA solution, through exhaustive search, is reduced to be in $O(R^U)$. However, it remains practically intractable, particularly for large U. For that, we resort in this article to a low-complexity heuristic algorithm, based on the received SINR, to determine user-RRH associations. As a matter of fact, user u is associated with RRH i^* whose radio signals are the best received: $i^* = \text{argmax}_i \ \Gamma_{ik}^u$. This heuristic maximizes users radio conditions and enhances network spectral efficiency. Note that, at this stage, the RRH-BBU mappings are assumed known. Afterward, considering the outputs of this UA sub-problem (*i.e.,* user association variables x_i^u), the RRH clusters may change in a way to minimize both the total transmission delay and the network power consumption. This directly impacts users radio conditions and can lead to user-RRH re-associations.

B. RC Sub-Problem

At this stage, assuming a given user association (*i.e.,* user association variables x_i^u are known), our problem ($\mathcal{P}$) comes down to the following RC sub-problem:

$$\underset{y}{\text{minimize}} \quad C(y) \tag{24}$$

$$\text{subject to} \quad (15) \text{ and } (17) \tag{25}$$

$$y_{ik}, B^k \in \{0,1\}, \forall i, \forall k \tag{26}$$

As x_i^u are known, the complexity to find the optimal RC solution, through exhaustive search, is reduced to be in $O(B_R)$. As in practice R is much smaller than U, and to reach jointly efficient solutions that reduce both the network power consumption and the total transmission delay, we propose in this work to obtain the optimal RC solutions through exhaustive search.

VI. Simulation Results

In this section, we evaluate the performance of our proposed approach. We also compare our optimal solution for the RC sub-problem with the no-clustering solution, where one BBU is exclusively dedicated to each RRH, and the grand coalition solution, where all RRHs are associated with a single BBU.

The simulation results were obtained using Matlab. For illustration, we consider a 7-cell network: a central RRH is surrounded by a ring of 6 immediately adjacent RRHs. We assume that users are uniformly distributed in the network. The channel gains are calculated using the Cost-231 Hata model. Simulations are repeated 250 times, and performance metrics are averaged and shown with 95% confidence intervals. The simulation parameters are summarized in Table I.

TABLE I
Simulation Parameters

Parameter	*Value*
α	0.5
β	0.5
$P_i, \forall i$	10 W
P^0	6.8 W
P^s	4.3 W
δ	4
λ	40 W
Cell radius	500 m
W	20 MHz
N_0	-174 dBm/Hz

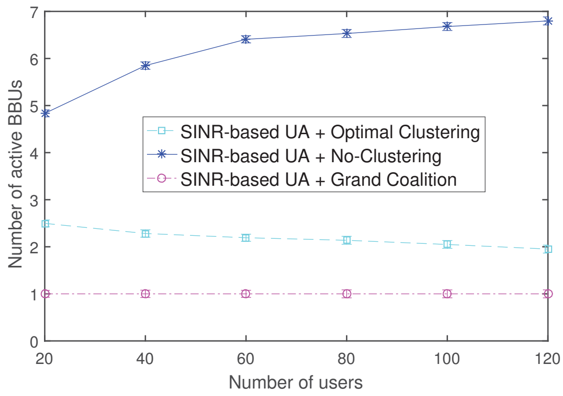

Fig. 2. Number of active BBUs as a function of the number of users

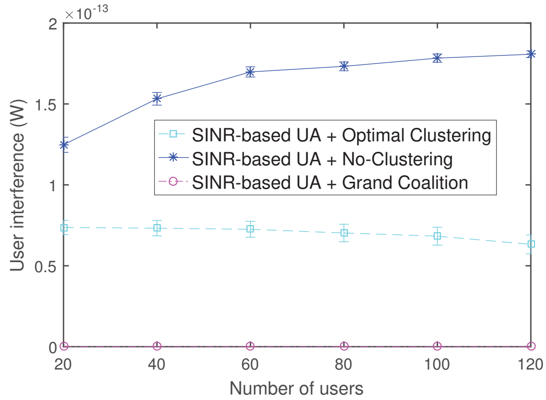

Fig. 3. User interference as a function of the number of users

We respectively depict in Fig. 2 and 3 the number of active BBUs and the user interference as a function of the number of users. When the grand coalition solution is used for the RC sub-problem, all the RRHs are clustered together leading to only one active BBU. Consequently, the users do not experience any interference, leading to very favorable radio conditions. In fact, as only one user per BBU is served at a time, there is no intra-cluster interference. Besides, since all the RRHs form a unique cluster, there is also no inter-cluster interference. Moreover, when the no-clustering solution is used for the RC sub-problem, the number of active BBUs is equivalent to the number of serving RRHs. As only efficient RRHs, with which at least one user is associated, are turned on, the number of active BBUs increases with the network load. While this solution provides the most radio resources to the users, it yields the highest interference level as illustrated in Fig. 3. The inter-cluster interference is then harmful and degrades the network spectral efficiency. Furthermore, when the optimal solution is used for the RC sub-problem, RRHs are clustered in a way to minimize the network power consumption and the total transmission delay. As a result, an efficient trade-off between radio resource availabilities and user radio conditions is achieved.

Figures 4 and 5 respectively show the user transmission delay and the C-RAN power consumption as a function of the number of users. When the grand coalition solution is used for the RC sub-problem, all the users compete for the same radio resource pool. Consequently, they experience the highest average transmission delay, despite their very favorable radio conditions. However, this solution leads to the lowest power consumption, as only one BBU is active. Further, when the no-clustering solution is used for the RC sub-problem, the most radio resources are made available to the users. Although they suffer from relatively high interference (cf. Fig. 3), the users perceive the lowest transmission delay. Nevertheless, this comes at the cost of the highest power consumption, as shown in Fig. 5. Moreover, when the optimal solution is used for the RC sub-problem, enough BBUs are activated so as to efficiently balance between low transmission delay and low power consumption. More precisely, at low and medium load conditions, our proposed solution provides very close user transmission delay to that when the no-clustering solution is used. In fact, although our solution activates less BBUs (cf. Fig. 2), it yields lower interference (cf. Fig. 3) and benefits from higher spectral efficiency. Furthermore, at high load conditions, the gap between the two solutions increases, since additional BBUs are activated when the no-clustering solution is used (cf. Fig. 2). As a matter of fact, the better radio conditions can not compensate for the larger radio resources availabilities, at high low conditions. However, our proposed solution constantly provides significantly lower power consumption in comparison with when the no-clustering is used. Besides, in comparison with when the grand coalition is used, our proposed solution provides lower user transmission delay but higher power consumption.

In addition, note that the weights α and β associated with the transmission delay and the power consumption costs can be tuned, so as to meet operator objectives (*i.e.,* devote more importance to the power consumption at the

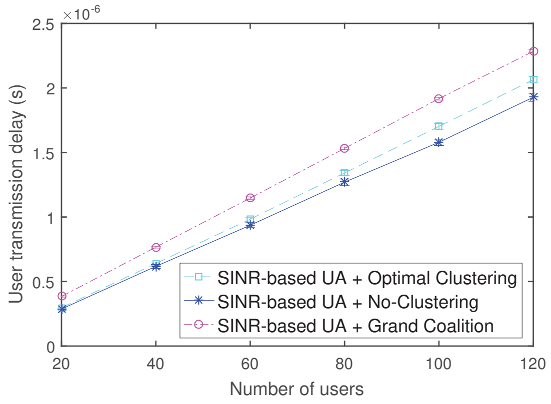

Fig. 4. User transmission delay as a function of the number of users

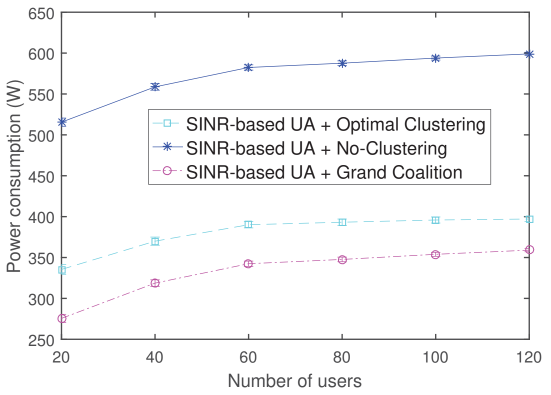

Fig. 5. C-RAN power consumption as a function of the number of users

cost of increased user transmission delay, or vice-versa).

Further, we respectively depict in Fig. 6 and 7 the network cost and the number of iterations needed to reach convergence as a function of the number of users. As we notice, our proposed solution jointly minimizes the total transmission delay and the C-RAN power consumption, or equivalently the network cost. In fact, our iterative approach reaches the best trade-off between the power consumption and the total transmission delay within few iterations. More precisely, the number of iterations needed to reach convergence increases with the number of users in the network, and is on average close to 10 at high load conditions.

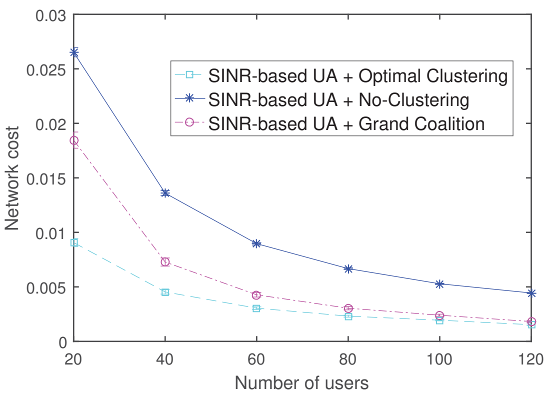

Fig. 6. Network cost as a function of the number of users

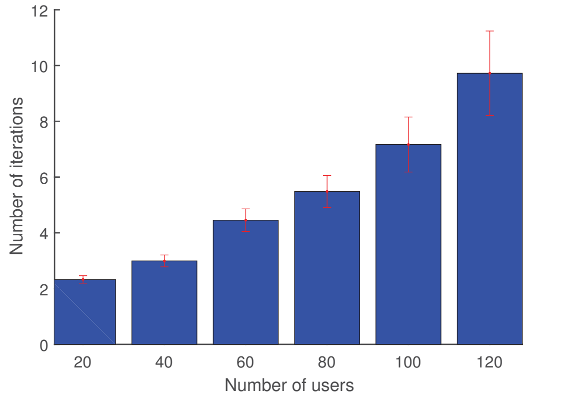

Fig. 7. Number of iterations as a function of the number of users

VII. Conclusion

In this paper, we have provided a framework for the joint user association and the RRH clustering problem. Our objective is to minimize both the network power consumption and the total transmission delay. To overcome the complexity of the joint problem, we have presented an iterative approach that allows reaching stable and jointly efficient solutions. The idea is to decouple our problem into two sub-problems, namely the user association (UA) sub-problem and the RRH clustering (RC) sub-problem, and to sequentially and iteratively solve them until convergence is achieved. A low-complexity heuristic based on the received SINR were used for the UA sub-problem, and an optimal algorithm based on exhaustive search were adopted for the RC sub-problem. In future work, multiple centralized and distributed UA and RC solutions will be proposed and integrated to our iterative approach.

References

[1] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016-2021 White paper, March 2017.

[2] J. Zuo, J. Zhang, C. Yuen, W. Jiang, and W. Luo, "Energy efficient user association for cloud radio access networks," *IEEE Access*, vol. 4, pp. 2429–2438, 2016.

[3] M. Awais, A. Ahmed, M. Naeem, M. Iqbal, W. Ejaz, A. Anpalagan, and H. S. Kim, "Efficient joint user association and resource allocation for cloud radio access networks," *IEEE Access*, vol. 5, pp. 1439–1448, 2017.

[4] H. Taleb, M. E. Helou, K. Khawam, S. Lahoud, and S. Martin, "Centralized and distributed rrh clustering in cloud radio access networks," in *2017 IEEE Symposium on Computers and Communications (ISCC)*, July 2017, pp. 1091–1097.

[5] K. Boulos, M. E. Helou, and S. Lahoud, "RRH Clustering in Cloud Radio Access Networks," in *Applied Research in Computer Science and Engineering (ICAR), 2015 International Conference on*, Oct 2015.

[6] K. Boulos, M. E. Helou, M. Ibrahim, K. Khawam, H. Sawaya, and S. Martin, "Interference-aware clustering in cloud radio access networks," in *2017 IEEE 6th International Conference on Cloud Networking (CloudNet)*, Sept 2017, pp. 1–6.

[7] M. Y. Lyazidi, N. Aitsaadi, and R. Langar, "Dynamic resource allocation for cloud-ran in lte with real-time bbu/rrh assignment," in *2016 IEEE International Conference on Communications (ICC)*, May 2016.

[8] X. Li, F. Jin, R. Zhang, and L. Hanzo, "Joint cluster formation and user association under delay guarantees in visible-light networks," in *2016 IEEE Global Communications Conference (GLOBECOM)*, Dec 2016.

[9] G. Auer, V. Giannini, C. Desset, I. Godor, P. Skillermark, M. Olsson, M. A. Imran, D. Sabella, M. J. Gonzalez, O. Blume, and A. Fehske, "How much energy is needed to run a wireless network?" *IEEE Wireless Communications*, vol. 18, no. 5, pp. 40–49, October 2011.