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Efficient Joint User Association and Resource Allocation for Cloud Radio Access Networks

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ABSTRACT Coordinated scheduling is an efficient resource allocation technique employed to improve the throughput, utilization, and energy efficiency of radio networks. This work focuses on the coordinated scheduling problem for cloud radio access network (CRAN). In particular, we consider the downlink of a CRAN where a central cloud performs the scheduling and synchronization of transmitting frames across the base stations (BSs). For each BS, the transmit frame is composed of several time/frequency slots called resource blocks (RBs). We formulate an optimization problem for joint users to BS association and resource allocation with an objective to maximize the overall network utilization under practical network constraints. The formulated problem is combinatorial and an optimal solution of such a problem can be obtained by performing an exhaustive search over all possible users-to-BSs assignments that satisfy the network constraints. However, the size of search space increases exponentially with the number of users, BSs, and RBs, thus making this approach prohibitive for networks of practical size. This work proposes an interference-aware greedy heuristic algorithm for the constrained coordinated scheduling problem. The complexity analysis of the proposed heuristic is also presented and performance is compared with the optimal exhaustive search algorithm. Simulation results are presented for various network scenarios which demonstrate that the proposed solution achieves performance comparable to the optimal exhaustive search algorithm.

INDEX TERMS Coordinated Scheduling, greedy algorithm, optimal and near optimal scheduling.

I. INTRODUCTION

5G cellular networks are expected to meet the challenges of increased traffic volume, very high data rates, limited available spectrum, a large number of users, and strict latency requirements [1], [2]. These challenges call for a paradigm shift in the traditional network system architecture. One progressive move to facilitate higher data rates and coverage in urban areas is to migrate from a single high-powered base station (BS) to heterogeneous networks with a large number of small cells of different sizes [3]. However, decreasing the cell size results in large scale inter-BS interference, especially when an underlying strategy is based on full spectrum reuse. In order to mitigate this interference, collaborative radio techniques such as coordinated multi-point (CoMP) [4] have been proposed. However, efficient CoMP algorithms such as joint transmission in the uplink and downlink require additional processing as well as a large amount of data transfer between different sites. This results in significant delays and therefore, suffers from a considerable performance loss with traditional X2 interface of LTE architecture [5]. Moreover, power consumption is another major concern for mobile operators since, radio access networks (RAN) constitute a major part of total power consumption of mobile radio networks.

To address these issues, a new type of RAN architecture was proposed and called as CRAN which stands for Centralized, Collaborative, Cloud and Clean RAN [6], [7]. CRAN divides the traditional BS into three parts namely remote radio heads (RRHs), the baseband unit (BBU) pool, and a high speed front haul communication link connecting RRH to the BBU cloud pool. In CRAN, various network intensive activities are centralized and moved into the BBU pool in the cloud such as baseband signal processing, precoding matrix calculation, channel state information estimation etc. The cloud is composed of numerous software defined virtual machines which are dynamically configurable, scalable, and re-allocatable on demand. On the other side, RRHs act as the soft relays and can compress and forward the received signals from the BBU. CRAN offers a number of advantages over traditional RAN architectures such as increased resource utilization, lower energy consumption, and decreased inter-base station interference through inter-base station coordination.

Most of the recent work on CRAN assumes signal-level coordination at the cloud which includes several joint strategies, i.e., beamforming, resource allocation, and signal processing [8]–[10]. However, such coordination needs collaborative sharing of all data streams among BSs connected to a cloud and thus, requires a large number of high-capacity backhaul communication links. In contrast, we consider the scheduling level coordination which is more practical to implement and at the same time, allows an efficient assignment of users to BSs. We consider the downlink of CRAN where a central processor (cloud) is connected to several single antenna BSs. The cloud is responsible for synchronization of transmitting frames and scheduling of the users across the BSs. The transmit frame of every BS consists of several time/frequency slots called resource blocks (RBs), all maintained at fixed transmit power. To avoid signal level coordination among the BSs, we consider practical constraints, i.e., each user can be connected to at most one BS at a given time. However, a user can occupy multiple RBs belonging to the frame of the same BS. Moreover, a single RB can serve one and only one user at a time.

Under fixed power transmission and above mentioned practical constraints, the problem of assigning users to BSs becomes a discrete optimization problem whose objective is to maximize a generic network-wide utility function. Such a problem can be solved by an exhaustive search over all possible candidate assignments (that satisfy practical constraints) of users to RBs. However, the exhaustive search is prohibitive for practical networks as the size of search space increases exponentially with the number of users, BSs, and RBs.

A. RELATED WORK

A number of published works on scheduling are based on a per-assigned association of users and BSs [11], [12]. The work in [11], proposed a classical proportionality fair scheduling on a per-BS basis. The proposed scheme optimizes the user schedule, beamforming vectors, and power spectra jointly while taking into account the inter-cell and intra-cell interference and fairness among the users. In [12], the authors proposed a coordinated scheduling technique for soft frequency reuse based wireless backhaul networks. The problem setup is a simple linear assignment problem as it assumes an equal number of users and RBs. The authors further showed that this problem can be solved by classical auction methodology [13]. The work in [14] proposed a dynamic resource allocation scheme for LTE CRAN. The authors modeled the resource and power allocation problem as a mixed integer linear problem and solved it using a branch and cut algorithm. In [15], the resource allocation problem in CRAN based public safety network (PSN) is modelled as an integer quadratic programming problem. Later on, a Generalized Benders Decomposition (GBD) based OFDM resource allocation algorithm is proposed to find out the solution.

In [16], authors proposed a frame work for dynamic coordinated scheduling CoMP in LTE-Advanced networks. The authors proposed that large scale coordination can be obtained through a layered approach in which a cluster of few cells is coordinated in first level, and clusters of coordinated cells are coordinated at a larger scale. The authors modeled both small scale and large scale coordination as optimization problems and then proposed heuristic algorithms for their solution. In [17], authors considered the joint cost effective resource allocation between in CRAN and mobile cloud computing (MCC). In [18], the authors maximized the system capacity in a highly dense CRAN through the usage of CoMP and opportunistic relay activation. Authors in [19] proposed a framework for the resource allocation and admission control problem in a two-tier OFDMA cellular network that is composed of a macrocell which is underlaid with CRAN of small cells. The work in [20] proposes a graph theoretic approach for coordinated scheduling problem. In the first step, the authors construct the binary scheduling graph where each vertex represents an association between users, BSs, and RBs. Next, authors formulated the problem as a maximum weight clique problem and proposed a heuristic method for its solution. However, the size of the adjacency matrix of scheduling graph grows quadratically with the product of a number of users, BSs, and RBs.

In summary, the above scheduling schemes do not address the scheduling level coordination for practical implementation and efficient assignment of users to BS.

B. CONTRIBUTIONS

The main contributions of this paper are summarized as under:

- This work solves the coordinated scheduling problem for the downlink of CRAN for any number of users, BSs, and RBs. The work maximizes the overall network utilization (expressed in terms of sum rate (bits/sec)) under the practical constraints.
- The work proposes an efficient heuristic solution based on an interference-aware greedy algorithm.
- The proposed solution is computationally efficient and is applicable for dense networks with large number of users, BSs, and RBs.
- The accuracy of the proposed solution is validated against a number of practical network scenarios. The simulation results demonstrate that the proposed solution performs very close to the optimal sum rate performance achieved by a brute force exhaustive search

algorithm. Moreover, the simulation results also show the efficiency of joint user-BS assignment and resource allocation for CRAN.

Notations: Throughout this paper, we use **A** to denote a matrix, **a** to denote a vector, and a or A to denote a scalar. Let $\mathcal{U}$ be a set, $|\mathcal{U}|$ denotes the cardinality of the set $\mathcal{U}$ and $\mathcal{P}(\mathcal{U})$ denotes its power set. The set $\mathcal{B} \times \mathcal{R}$ denotes the Cartesian product of sets $\mathcal{B}$ and $\mathcal{R}$.

The rest of the paper is organized as follows, Section 2 describes the system model and problem formulation. Section 3 discusses the proposed solution based on a greedy heuristic. Simulation results are discussed in Section 4. Finally, the paper concludes in Section 5.

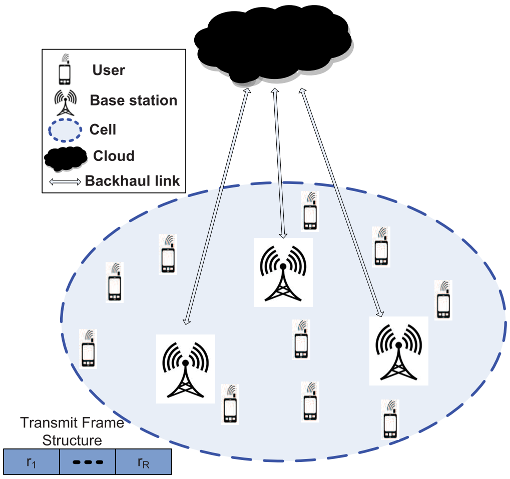

FIGURE 1. Generalized cloud-enable network consisting of 3 BSs and 10 users. The cloud is connected to BSs through low capacity backhaul communication links.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. SYSTEM MODEL

Fig. 1 shows a generalized CRAN configuration considered in this work. The CRAN consists of a central cloud which is connected to B single antenna BSs and serves a total of U users. Let $\mathcal{B} = \{b_1, b_2, \cdots, b_B\}$ denotes the set of all BSs in the network and $\mathcal{U} = \{u_1, u_2, \cdots, u_U\}$ denotes the set of all users. The transmit frame of each BS consists of R resource blocks as denoted by the set $\mathcal{R} = \{r_1, r_2, \cdots, r_R\}$, where each RB is maintained at fixed transmit power P_t. The total number of RBs in the network is $R_t = R \times B$. The cloud manages the scheduling of users as well as synchronization of all transmit frames. The scheduling information is communicated to the BSs through backhaul communication links. The data rate (bits/sec) of a communication link depends on the signal-to-interference plus noise ratio (SINR) seen by the receiver. For a particular receiver located at some point x in space (usually, on the plane), the simplest SINR model is given as

$$\gamma(x) = \frac{P}{N + I}, \quad (1)$$

where γ is the SINR, P is the power of the incoming signal of interest, I is the power of other interfering signals, and N is noise power. In the case of a CRAN, SINR of the user (receiver) u when connected to the RB r of BS b is given as

$$\gamma^u_{br} = \frac{P_{br}.\left|h^u_{br}\right|^2}{\Gamma(\sigma^2 + \sum_{b' \neq b} P_{b'r}\left|h^u_{b'r}\right|^2)}, \forall b \in \mathcal{B}, \forall r \in \mathcal{R}, \quad \forall u \in \mathcal{U} \quad (2)$$

where $P_{br} = P_t$ is the transmit power associated to the RB r of BS b, h^u_{br} denotes the fading random coefficient of Rayleigh distribution, σ^2 is the Gaussian noise variance, and Γ is the SINR gap. Orthogonal RBs are assumed in this work as demonstrated by the denominator term $\sum_{b' \neq b} P_{b'r}\left|h^u_{b'r}\right|^2$ which shows that for a user u connected to a RB r of BS b, the interference is only experienced from the RBs with the same index r across different BSs.

A list of symbols and their description is given in Table 1.

B. PROBLEM FORMULATION

In order to avoid signal level coordination among the connected BSs, this work considers two practical constraints for the coordinated scheduling problem for CRAN.

- C1: Every user in the network must be connected to at-most one BS at a time, however, can occupy multiple RBs within the transmit frame of that BS.
- C2: Every RB in the network must be able to serve at most one user at a time.

Given the sets $\mathcal{U}$, $\mathcal{B}$, and $\mathcal{R}$, $\mathcal{U} \times \mathcal{B}$ denotes the set of all possible associations between users and BSs, whereas $\mathcal{B} \times \mathcal{R}$ denotes the set of all possible associations between BSs and RBs. Moreover, $\mathcal{A} = \mathcal{U} \times \mathcal{B} \times \mathcal{R}$ is the set of all possible associations between users, BSs, and RBs and $|\mathcal{A}| = U \cdot B \cdot Z$. The power set of $\mathcal{A}$, i.e., $\mathcal{P}(\mathcal{A})$ denotes the set of all possible schedules regardless of the scheduling scheme satisfying constraints C1 and C2 or not.

Each individual schedule $\mathcal{S} \in \mathcal{P}(\mathcal{A})$ can be written as $\mathcal{S} = \{s_1, s_2, \cdots, s_{|s|}\}$, i.e., a set of associations where each individual association s_i is a triplet $(u, b, r) \in \mathcal{A}$. This paper considers the following network-wide utility maximization problem:

$$\hat{\mathbf{S}} = \arg\max_{S \in \mathcal{P}(\mathcal{A})}\{\sum_{u,b,r} \alpha_{ubr} X_{ubr}\} \quad (3)$$

subject to

$$Y_{ub} = \min(\sum_r X_{ubr}, 1), \forall (u, b) \in \mathcal{U} \times \mathcal{B} \quad (4)$$

$$\sum_b Y_{ub} \leq 1, \quad \forall u \in \mathcal{U}, \quad (5)$$

$$\sum_u X_{ubr} = 1, \quad \forall (b, r) \in \mathcal{B} \times \mathcal{R}, \quad (6)$$

$$X_{ubr}, Y_{ub} \in \{0, 1\}, \forall (u, b, r) \in \mathcal{U} \times \mathcal{B} \times \mathcal{R} \quad (7)$$

Equation (3) shows that the objective is to find a schedule $\hat{\mathbf{S}}$ that achieves a maximum value of network utilization among all feasible schedules (that satisfy C1 and C2) in $\mathcal{P}(\mathcal{A})$. The utilization of a schedule $\mathcal{S} \in \mathcal{P}(\mathcal{A})$ is the sum of individual

TABLE 1. List of symbols and their description.

Symbol	Description
$\mathcal{U},\mathcal{B},\mathcal{R}$	Set of users, BSs and RBs per BS
U,B,R	Total no. of users, BSs and RBs per BS respectively
γ	SINR
σ^2	Variance of background noise
Γ	SINR Gap
P_t	Maximum transmit power per RB
$\mathbf{H}$	A matrix of dimensions $U \times B \times R$ which contains fading coefficients of all possible channels in the system
$\mathbf{S}$	Matrix of dimensions $U \times B \times R$ which contains SINR values for all possible channels in the system
$\mathbf{A}$	Matrix of dimensions $U \times B \times R$ which contains data rates (bps) of all possible channels in the system
a'	sum rate utilization (bps) of a schedule
$\mathbf{\Omega}$	local binary schedule matrix of dimensions $U \times B \times R$
a	Overall network utilization (sum rate in bits/sec) achieved by the algorithm
$\hat{\mathbf{A}}$	Optimal Schedule matrix: a binary matrix whose entry at index u,b,r is 1 if a user u is assigned to RB r of BS b and zero otherwise
Λ	Vector which represents the indexes of users to be excluded from Argmax function calculation
$\mathbf{A}^{'}$	Matrix which contains all values of $\mathbf{A}$, except the values whom user indexes are stored in Λ
$[u,b,r]$	Triplet that represents the indexes of user, BS and RB respectively
$\mathcal{S}\backslash s$	denotes all elements of set $\mathcal{S}$ excluding the element s
$[\Lambda,u]$	concatenation operation of vector Λ with scalar u
$\mathbf{u}$	A vector of size U that contains the values of a column of $\mathbf{A}$ matrix
Rayleigh_rand()	Returns a random number from Rayleigh distribution
dec2bin(x,n)	function which returns the binary representation of a decimal number x with atleast n bits
reshape(x,m,n,p)	returns an m-by-n-by-p array whose elements are taken column wise from x
Argmax$(\mathbf{A}^{'})$	Function which returns the triplet $[u,b,r]$ for maximum value of $\mathbf{A}^{'}$
argmax$(\mathbf{u})$	Function which returns the user index of maximum value of vector $\mathbf{u}$

associations in $\mathcal{S}$. To show whether an association s_i exists or not, X_{ubr} is a binary variable which is 1 if a user $u \in \mathcal{U}$ is assigned to RB $r \in \mathcal{R}$ of BS $b \in \mathcal{B}$, and zero otherwise, Y_{ub} is another random variable which is 1 when a user u is assigned to a BS b and zero otherwise, α_{ubr} denotes the utilization of an association s_i. In this work, α_{ubr} is expressed as the data rate (bits/sec) of a communication link established when a user u is assigned RB r of BS b. Mathematically,

$$\alpha_{ubr} = \log_2(1 + \gamma^u_{br}). \tag{8}$$

The optimal scheduling problem of (3) becomes a sum-rate maximization problem. The constrained optimization is performed over variables X_{ubr} and Y_{ub}, where (4) and (5) correspond to the constraint C1 while (6) corresponds to constraint C2 of the optimization problem. The optimization problem in (3) to (7) is combinatorial in nature. Finding a global optimum solution to this problem requires to perform an exhaustive search over all possible schedules in $\mathcal{P}(\mathcal{A})$ which is clearly infeasible for any network of practical size because $|\mathcal{P}(\mathcal{A})| = 2^{|\mathcal{A}|}$.

The next section proposes a computationally efficient and accurate heuristic solution for the coordinated scheduling problem given in (3) to (7).

III. PROPOSED HEURISTIC FOR COORDINATED SCHEDULING

We propose a heuristic solution to solve the problem in (3) for coordinated scheduling. The proposed solution is based on an interference aware greedy algorithm. In addition, the problem in (3) is solved using optimal brute force algorithm based on an exhaustive search. The performance comparison of heuristic solution and optimal brute force algorithm is provided to demonstrate the effectiveness of proposed solution.

The common inputs to both algorithms are vectors $\mathcal{U}$, $\mathcal{B}$ and $\mathcal{R}$ which denote the set of all users, BSs, and RBs per base station respectively. The cardinality of these sets is represented by the scalars U, B, and R which denote respectively, the total number of users, BSs, and RBs per BS. In addition, σ^2 denotes the variance of background noise and Γ is the SINR gap. Under fixed power transmission constraint, the RBs of all BSs are maintained at fixed transmit power denoted by P_t.

A. GREEDY HEURISTIC SOLUTION

The proposed greedy heuristic solution given in Algorithm 1 is divided into four execution phases.

Execution Phase 1 (Steps 8 to 10): The execution phase 1 consists of computing the channel matrix $\mathbf{H}$ of dimensions U, B, R. An entry H_{ubr} is a complex random number from Rayleigh distribution and denotes the gain of a complex channel established as a result of an association between user u and RB r of BS b. In the next step, matrix $\mathbf{S}$ is computed using (2), which contains the SINR values of all possible channels in the system. Finally, matrix $\mathbf{A}$ is computed using (8) which represents the data rates (bits/sec) of all possible channels.

Execution Phase 2 (Steps 12 to 18): In order to guarantee minimum network service for all $U < R_t$ users, this phase ensures that every user in the network is assigned at least one RB. The *for loop* runs for U iterations and during each iteration, the matrix $\mathbf{A}^{'}$ is obtained which consists of all elements of $\mathbf{A}$, except the elements whose user indexes are stored

Algorithm 1 Proposed Greedy Heuristic Algorithm for Coordinated Scheduling

1: **Inputs:**
2: $U,\ B,\ R,\ \sigma^2,\ \Gamma, P_t$
3: $\mathcal{U} = \{1, \cdots, U\}, \mathcal{B} = \{1, \cdots, B\}, \mathcal{R} = \{1, \cdots, R\}$
4: **Initialize:** $\forall u \in \mathcal{U}, b \in \mathcal{B}, r \in \mathcal{R}$
5: $\mathbf{H}_{ubr} \leftarrow 0,\ \mathbf{S}_{ubr} \leftarrow 0,\ \mathbf{A}_{ubr} \leftarrow 0,\ \hat{\mathbf{A}}_{ubr} \leftarrow 0$
6: $\Lambda \leftarrow \phi, a \leftarrow 0$
7: **Execution Phase 1:** $\forall u \in \mathcal{U}, b \in \mathcal{B}, r \in \mathcal{R}$
8: $\mathbf{H}_{ubr} \leftarrow$ Rayleigh_rand()
9: $\mathbf{S}_{ubr} \leftarrow \frac{P_t.|\mathbf{H}_{ubr}|^2}{\Gamma.\left(\sigma^2 + \sum_{b' \in \mathcal{B} \setminus b} P_t.|\mathbf{H}_{ub'r}|^2\right)}$
10: $\mathbf{A}_{ubr} \leftarrow \log_2(1 + \mathbf{S}_{ubr})$
11: **Execution Phase 2:**
12: **for** $x \leftarrow 1, U$ **do**
13: $\quad \mathbf{A}'_{ubr} \leftarrow \mathbf{A}_{ubr},\ \forall u \in \mathcal{U} \setminus \Lambda, b \in \mathcal{B}, r \in \mathcal{R}$
14: $\quad [u, b, r] \leftarrow$ Argmax$(\mathbf{A}')$
15: $\quad \mathbf{A}_{ub'r'} \leftarrow 0,\ \forall\, b' \in \mathcal{B} \setminus b, r' \in \mathcal{R}$
16: $\quad \mathbf{A}_{u'br} \leftarrow 0,\ \forall\, u' \in \mathcal{U} \setminus u$
17: $\quad \Lambda \leftarrow \{\Lambda, u\}$
18: **end for**
19: **Execution Phase 3:**
20: **for** $x \leftarrow 1, B$ **do**
21: $\quad$ **for** $y \leftarrow 1, R$ **do**
22: $\quad\quad \mathbf{u} \leftarrow \mathbf{A}_{uxy},\ \forall\, u \in \mathcal{U}$
23: $\quad\quad [u] \leftarrow$ argmax$(\mathbf{u})$
24: $\quad\quad \mathbf{A}_{u'xy} \leftarrow 0,\ \forall\, u' \in \mathcal{U} \setminus u,$
25: $\quad$ **end for**
26: **end for**
27: **Execution Phase 4:** $\forall u \in \mathcal{U}, b \in \mathcal{B}, r \in \mathcal{R}$
28: $\hat{\mathbf{A}}_{ubr} \leftarrow 1,\ $ if $\mathbf{A}_{ubr} \neq 0;\ a \leftarrow \sum_{ubr} \mathbf{A}$
29: **Outputs:** $\hat{\mathbf{A}},\ a$

in vector Λ. Next, the Argmax$(\mathbf{A}')$ is executed which returns the indexes $[u, b, r]$ of maximum value of $\mathbf{A}'$. Initially, the vector Λ is empty, therefore, all elements of $\mathbf{A}$ are stored in $\mathbf{A}'$ and corresponding indexes of maximum value are obtained. The triplet $[u, b, r]$ returned by the Argmax function denotes the user, BS, and RB indexes of a channel with maximum data rate (bits/sec). The value at indexes $[u, b, r]$ in matrix $\mathbf{A}$ is preserved in order to mark an association between user u and RB r of BS b. Once a user u is assigned to BS b, it cannot be assigned to any other BS (i.e., constraint C1). To do so, step 15 assigns zero to all entries of $\mathbf{A}$ with user index equal to u and BS index other than b. Similarly, to satisfy C2, step 16 assigns zero to entries of $\mathbf{A}$ with BS and RB indexes equal to b and r, respectively and user index other than u. In the next step (step 17), the user index u returned by Argmax function is concatenated to vector Λ, i.e., added to the list of users which are to be excluded from the Argmax function in the next iteration.

Execution Phase 3 (Steps 20 to 26): During this phase, the remaining $R_t - U$ RBs are assigned. The outer *for loop* runs for B iterations while the inner *for loop* runs for R iterations. During each iteration, for a particular value of loop variables $x \in \mathcal{B}$ and $y \in \mathcal{R}$, a vector $\mathbf{u}$ is obtained which consists of all values of $\mathbf{A}$ with BS and RB indexes equal to x and y respectively. The argmax $(\mathbf{u})$ function returns the user index u of maximum value of $\mathbf{u}$. The corresponding entry in $\mathbf{A}$ at indexes u, x, and y is preserved to mark an association between user u and RB y of BS x. To make sure that constraints C1 and C2 are satisfied for this association, the remaining entries of $\mathbf{A}$ are set to zero in step 24.

Execution Phase 4 (Steps 28 to 29): This phase computes the output binary schedule matrix $\hat{\mathbf{A}}$. A=1 at index ubr indicates an association between user u and RB r of BS b whereas, a A=0 indicates no association. Finally, the overall sum rate a of the complete network is computed by adding all entries of $\mathbf{A}$.

B. OPTIMAL BRUTE FORCE ALGORITHM

The optimal brute force algorithm can be divided in two execution phases. Algorithm 2 lists the main steps of an optimal brute force algorithm based on an exhaustive search.

Execution Phase 1: This phase for optimal brute force algorithm is same as the execution phase 1 of Algorithm 1 given in Section III-A.

Execution Phase 2: During this phase, the *for loop* runs for $2^{U \cdot B \cdot R}$ iterations, equal to the size of search space. During each iteration, a local binary schedule matrix Ω of dimensions U, B, R is generated and tested for constraints C1 and C2. If both constraints are satisfied for this matrix, a local rate matrix $\mathbf{A}'$ is computed by performing a dot product of matrices Ω and $\mathbf{A}$. The local sum rate a' is obtained by adding all the individual values of $\mathbf{A}'$. If the value of a' is greater than the overall sum rate a, then the value of a is replaced by a' and local binary schedule Ω becomes the optimal schedule $\hat{\mathbf{A}}$. This approach is clearly not feasible for practical sized networks as the number of C1, C2 evaluations is exponential to the network size.

C. COMPLEXITY ANALYSIS

The main advantage of the proposed heuristic algorithm explained in Section III-A lies in its low computational complexity. The complexity is measured in terms of flops[1] [21]. The initialization phase of Algorithm 2 has complexity equal to $4UBR + 1$ flops. The numerator term of step 9 has complexity of $5UBR$ flops whereas, the denominator term has a complexity of $UBR(5B + 6)$ flops. The total complexity of step 9 is $UBR(5B + 12)$. In total, the execution phase 1 (steps 8 to 10) takes $UBR(5B + 14)$ flops. The overall complexity of execution phase 2 (steps 12 to 18) is $U(2UBR + U + (B - 1)R)$. Execution phase 3 (steps 20 to 26) has complexity approximately $BR(3U - 1)$. The complexity of

[1]A flop is defined as a real floating point operation. A real addition, multiplication or division is counted as one flop. A complex addition takes two flops and a complex multiplication has four flops. Addition or removal of an element from a set takes one flop. The logical operator (e.g., comparison) takes one flop. The $\log_2(x)$ operator takes two flops.

Algorithm 2 :Brute Force Algorithm for Coordinated Scheduling

Inputs:
$U,\ B,\ R,\ \sigma^2,\ \Gamma, P_t$
$\mathcal{U} = \{1, \cdots, U\}$
$\mathcal{B} = \{1, \cdots, B\}$
$\mathcal{R} = \{1, \cdots, R\}$
Initialize: $\forall u \in \mathcal{U}, b \in \mathcal{B}, r \in \mathcal{R}$
$\mathbf{H}_{ubr} \leftarrow 0$
$\mathbf{S}_{ubr} \leftarrow 0$
$\mathbf{A}_{ubr} \leftarrow 0,\ \hat{\mathbf{A}}_{ubr} \leftarrow 0$
$\Omega_{ubr} \leftarrow 0, a \leftarrow 0$
Execution Phase 1: $\forall u \in \mathcal{U}, b \in \mathcal{B}, r \in \mathcal{R}$
$\mathbf{H}_{ubr} \leftarrow$ Rayleigh_rand()
$\mathbf{S}_{ubr} \leftarrow \frac{P_t.|\mathbf{H}_{ubr}|^2}{\Gamma.\left(\sigma^2 + \sum_{b' \in \mathcal{B} \setminus b} P_t.|\mathbf{H}_{ub'r}|^2\right)}$
$\mathbf{A}_{ubr} \leftarrow \log_2(1 + \mathbf{S}_{ubr})$
Execution Phase 2:
for $x \leftarrow 0, 2^{U \cdot B \cdot R} - 1$ **do**
  $a' \leftarrow 0$
  $v \leftarrow \mathrm{dec2bin}(x, U \cdot B \cdot R)$
  $\Omega \leftarrow \mathrm{reshape}(v, U, B, R)$
  check C1, C2 constraints (3) - (5) on Ω
  if C1, C2 satisfied **then**
    $\mathbf{A}'_{ubr} \leftarrow \Omega_{ubr} \cdot \mathbf{A}_{ubr}\ , \forall u \in \mathcal{U}, b \in \mathcal{B}, r \in \mathcal{R}$
    $a' \leftarrow \sum_{ubr}(\mathbf{A}')$
    if $a' > a$ **then**
      $a \leftarrow a'$
      $\hat{\mathbf{A}}_{ubr} \leftarrow \Omega_{ubr}\ , \forall u \in \mathcal{U}, b \in \mathcal{B}. r \in \mathcal{R}$
    end if
  end if
end for
Outputs: $\hat{\mathbf{A}},\ a$

execution phase 4 (steps 28 and 29) is $3UBR$. Therefore, the total number of flops required by the proposed algorithm are:

$$\begin{aligned}\text{No. of flops} &\approx (4UBR + 1) + UBR(5B + 14) + 3UBR \\ &\quad + U(2UBR + U + (B-1)R) + BR(3U - 1) \\ &\approx O(UBR + U^2 + UB^2R).\end{aligned}$$

From the above complexity analysis, we can conclude that the proposed interference aware greedy solution has a polynomial time complexity with respect to number of users, BSs, and RBs. In contrast, the computational complexity of exhaustive search Algorithm II is $O(2^{UBR})$.

IV. SIMULATION RESULTS

This section shows the performance of the proposed heuristic algorithm for coordinated scheduling. The considered CRAN downlink scenario is similar to Fig. 1 and the optimization is performed for sum rate (bits/sec) maximization problem (3). In order to evaluate the performance of proposed algorithm from various aspects, the number of users, BSs, and RBs has been kept variable, whereas additional simulation parameters are summarized in Table 2. The sum rate results reported in this section are the average results of Monte Carlo simulations. For a number of network configurations, the sum rate of the proposed heuristic is also compared with the one obtained from optimal coordinated scheduling based on exhaustive search (Algorithm 2).

TABLE 2. Main simulation parameters of Algorithm 1 .

Parameter	Value
No. of BSs (B)	variable
No. of RBs (R)	variable
No. of Users (U)	variable
Maximum transmit power per RB (P_t)	−42.60dBm/Hz
Background Noise power	−168.60dBm/Hz
SINR Gap (Γ)	0dB
Bandwidth	1MHz
Path loss model	Rayleigh
Channel Estimation	Perfect

A. AN ILLUSTRATION OF EXECUTION OF PROPOSED HEURISTIC ALGORITHM

Fig. 2 shows an illustration of execution of the proposed heuristic algorithm (Algorithm 1) for coordinated scheduling. A CRAN configuration consisting of three users, two BSs, and two RBs per BS is considered for execution. Fig. 2 (a) demonstrates the structure of $\mathbf{A}$ matrix such that the rows represent the elements of set $\mathcal{U}$, whereas the columns represent the elements of set $\mathcal{B} \times \mathcal{R}$.

Fig. 2 (b) demonstrates the steps 12 to 14 of first iteration of execution phase 2. Initially, the vector Λ is empty, therefore, matrix $\mathbf{A}'$ contains all elements of $\mathbf{A}$. The function Argmax($\mathbf{A}'$) returns the index triplet $[u, b, r] = [1, 3, 2]$ for maximum value of $\mathbf{A}'$. The value at these indexes is preserved in $\mathbf{A}$ to mark an association between user u_1 and RB r_2 of BS b_3. Fig. 2 (c) shows the execution of steps 15 and 16 which correspond to the constraints C1 and C2. To satisfy constraint C2, the column (RB) b_3r_2 is marked with zeros for all users except the user u_1. Similarly, to satisfy C1, the row u_1 is marked with zero for all columns (RBs) except the ones that belong to BS b_3. The row u_1 is concatenated with the vector Λ, i.e., excluded from Argmax function in the next iteration. Figs. 2 (d) to 2 (g) demonstrate the update of $\mathbf{A}$ matrix during the remaining iterations of execution phase 2. At the end of execution phase 2, the RBs b_1r_2, b_2r_1 and b_3r_2 have been assigned to users u_1, u_2 and u_3, respectively. The remaining RBs are assigned by execution phase 3 (steps 20 to 26) such that for each column (RB), the maximum entry is preserved to mark an association, whereas, the remaining entries are set to zero. This situation is demonstrated in Fig. 2 (h). Finally, Fig. 2 (i) shows the outputs of the algorithm computed by execution phase 4.

	B					
	b_1		b_2		b_3	
U	r_1	r_2	r_1	r_2	r_1	r_2
u_1	0.22	0.04	0.49	0.01	4.61	5.47
u_2	0.05	3.01	3.13	0.02	2.95	3.98
u_3	2.50	3.05	1.98	0.26	2.68	4.04

(a) **Execution Phase 1** Step 9. Matrix $\mathbf{A}$ for $U = 3, B = 3, R = 2$. The rows correspond to the elements of $\mathcal{U}$ whereas, columns correspond to the elements of set $\mathcal{B} \times \mathcal{R}$

	B					
	b_1		b_2		b_3	
U	r_1	r_2	r_1	r_2	r_1	r_2
u_1	0.22	0.04	0.49	0.01	4.61	5.47
u_2	0.05	3.01	3.13	0.02	2.95	3.98
u_3	2.50	3.05	1.98	0.26	2.68	4.04

(b) **Execution Phase 2** Steps 11 to 13. $x = 1$, initially Λ is empty hence $\mathbf{A}^{'} = \mathbf{A}$. Argmax($\mathbf{A}^{'}$) returns indexes $[u, b, r] = [1, 3, 2]$ for maximum value of $\mathbf{A}$ i.e. 5.47

	B					
	b_1		b_2		b_3	
U	r_1	r_2	r_1	r_2	r_1	r_2
u_1	0.00	0.00	0.00	0.00	4.61	5.47
u_2	0.05	3.01	3.13	0.02	2.95	0.00
u_3	2.50	3.05	1.98	0.26	2.68	0.00

(c) Steps 14 to 16. RB b_3r_2 is assigned to user u_1. To satisfy C1 and C2, all RBs except those of b_3 are marked zero for u_1 and RB b_3r_2 is marked zero for all users except u_1. $\Lambda = \{1\}$.

	B					
	b_1		b_2		b_3	
U	r_1	r_2	r_1	r_2	r_1	r_2
u_1	0.00	0.00	0.00	0.00	4.61	5.47
u_2	0.05	3.01	3.13	0.02	2.95	0.00
u_3	2.50	3.05	1.98	0.26	2.68	0.00

(d) Steps 11 to 13. $x = 2$, $\Lambda = \{1\}$ therefore $\mathbf{A}^{'}$ contains all elements of $\mathbf{A}$ except the elements for u_1 (i.e. the 1st row). The argmax($\mathbf{A}^{'}$) returns indexes $[u, b, r] = [2, 2, 1]$ of maximum value of $\mathbf{A}$ i.e. 3.13.

	B					
	b_1		b_2		b_3	
U	r_1	r_2	r_1	r_2	r_1	r_2
u_1	0.00	0.00	0.00	0.00	4.61	5.47
u_2	0.00	0.00	3.13	0.02	0.00	0.00
u_3	2.50	3.05	0.00	0.26	2.68	0.00

(e) Steps 14 to 16. RB b_2r_1 assigned to user u_2. To satisfy C1 and C2, all RBs except those of b_2 are marked zero for u_2 and RB b_2r_1 is marked zero for all users except u_2. $\Lambda = \{1, 2\}$.

	B					
	b_1		b_2		b_3	
U	r_1	r_2	r_1	r_2	r_1	r_2
u_1	0.00	0.00	0.00	0.00	4.61	5.47
u_2	0.00	0.00	3.13	0.02	0.00	0.00
u_3	2.50	3.05	0.00	0.26	2.68	0.00

(f) Steps 11 to 13. $x = 3$, $\Lambda = \{1, 2\}$ therefore $\mathbf{A}^{'}$ contains all elements of $\mathbf{A}$ except the elements for u_1 and u_2 (row 1 and 2). The argmax($\mathbf{A}^{'}$) returns indexes $[u, b, r] = [3, 1, 2]$ for maximum value of $\mathbf{A}$ i.e.3.05.

	B					
	b_1		b_2		b_3	
U	r_1	r_2	r_1	r_2	r_1	r_2
u_1	0.00	0.00	0.00	0.00	4.61	5.47
u_2	0.00	0.00	3.13	0.02	0.00	0.00
u_3	2.50	3.05	0.00	0.00	0.00	0.00

(g) Steps 14 to 16. The RB b_1r_2 is assigned to u_3. To satisfy C1 and C2 all RBs except those of b_1 are marked zero for u_3 and the RB b_1r_2 is marked zero for all users except u_3. Execution phase 2 terminates here. All three users have been assigned at least one RB

	B					
	b_1		b_2		b_3	
U	r_1	r_2	r_1	r_2	r_1	r_2
u_1	0.00	0.00	0.00	0.00	4.61	5.47
u_2	0.00	0.00	3.13	0.02	0.00	0.00
u_3	2.50	3.05	0.00	0.00	0.00	0.00

(h) **Execution Phase 3**: The remaining RBs are assigned by Steps 19 to 25. The RB b_1r_1(1st Column) has a maximum value at row u_3 hence it is assigned to user u_3. In a similar manner, the RBs $b_2r_2$and b_3r_1 are assigned to users u_2 and $u_1$respectively.

	B					
	b_1		b_2		b_3	
U	r_1	r_2	r_1	r_2	r_1	r_2
u_1	0	0	0	0	1	1
u_2	0	0	1	1	0	0
u_3	1	1	0	0	0	0

(i) **Execution Phase 4:** Steps 27, 28. $\hat{\mathbf{A}}$ matrix, Total network utilization $a = 18.78$

FIGURE 2. An Illustrative example showing the execution of Algorithm 1 for a CRAN consisting of $U = 3, B = 3$ and $R = 2$.

B. PERFORMANCE ANALYSIS

Fig. 3 reports the sum rate versus the number of users (U) for a CRAN that consists of 2 BSs and 2 RBs per BS. The figure first reveals the increasing trend of sum rate with U. Moreover, the performance gap between the optimal scheduling using an exhaustive search (Algorithm II) and the proposed heuristic (Algorithm I) is considerable for a large values of U, especially when $U > R_t$. This is due to the fact that for a large values of U, the interference becomes significantly large. Therefore, the role of coordinated scheduling becomes more pronounced as an interference mitigation technique. In addition, when $U > R_t$, some of the users remain unassigned to RBs which results in poor overall network utilization.

Fig. 4 plots the sum rate versus the number of RBs per BS for a CRAN that consists of 2 users and 2 BSs. Given a constant value of U and B, the sum rate increases with R as the total RBs, $R_t = B.R$ available to the users increase which increases the chance of better network utilization. The results demonstrate that the proposed heuristic covers the search space (of size 2^{UBR}) well and performs close to the optimal scheduling by exhaustive search.

Fig. 5 quantifies the performance of the proposed heuristic solution for a considerably larger CRAN. The sum rate is plotted as a function of U in a CRAN consisting of 10 BSs and variable RBs per BS ranging from $R = 20$ to 50. It is observed that for a fixed value of U and B, the sum rate increases with the increase in R. Moreover, given a fixed value of B and R, the sum rate increases with U. The figure also shows that the proposed heuristic achieves a fairly large sum rate, whereas, performing an exhaustive search for network of such complexity is clearly not feasible.

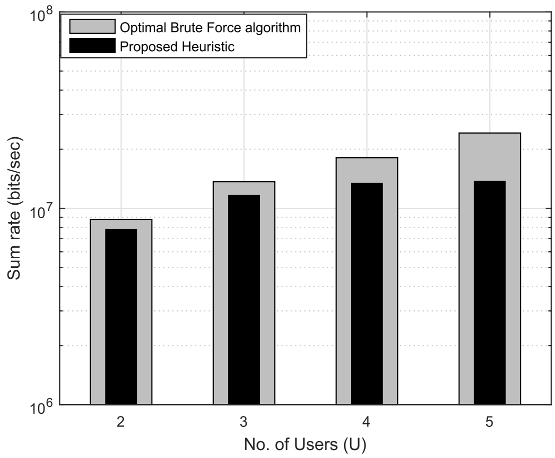

FIGURE 3. Sum Rate (bits/sec) versus the number of users (U). The number of BSs (B) is 2 and number of RBs per BS (R) is 2.

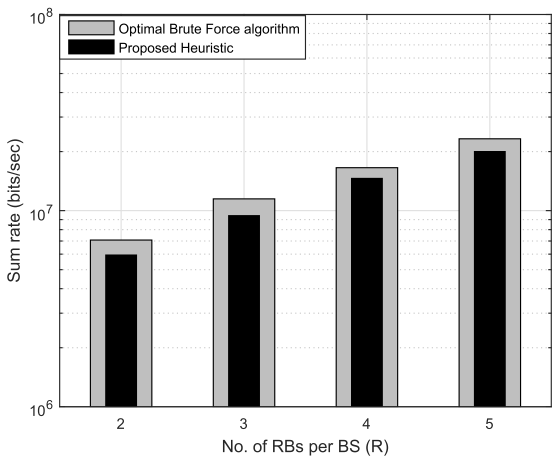

FIGURE 4. Sum rate (bits/sec) versus the number of RBs (R). The number of BSs (B) is 2 and the number of users (U) is 2.

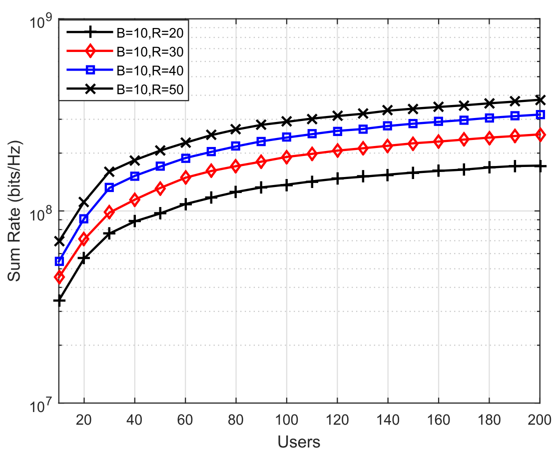

FIGURE 5. Sum rate (bits/sec) versus the number of users (U). The number of BSs (B) is 10 and the number of RBs (R) is variable from R=20 to 50.

Fig. 6 shows the sum rate results as a function of U for a CRAN consisting of variable number of BSs and 10 RBs per BS. For a given value of R and B, the result reveals that the sum rate increases with U. The result also shows that for a fixed value of U and R, the sum rate decreases with

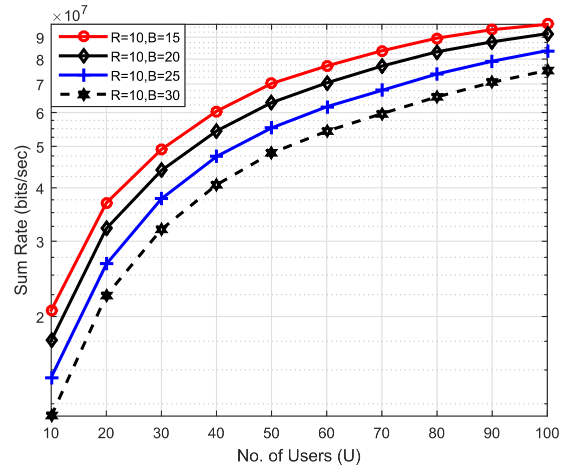

FIGURE 6. Sum rate (bits/sec) versus the number of users (U). The number of RBs (R) is 10 and the number of BSs (B) is variable from B=15 to 30.

increase in the number of BSs B. This phenomenon is due to the fact that the total interference seen by the observer u (the denominator term of (2)) increases with B. Since, a user can be only assigned to a single BS at a time (constraint C1), hence, the total network utilization decreases.

V. CONCLUSIONS

This work considered the coordinated scheduling problem in the downlink of CRAN. The user-to-BS assignment problem is modeled as a combinatorial optimization problem. The objective is to maximize a generic network utility expressed as sum rate (bits/sec) under the practical constraint, i.e., a user cannot be served by more than one BS; however, it can be assigned to multiple RBs within the transmit frame of each BS. Moreover, a RB can be assigned to only one user at a time. An optimal solution of such an optimization problem can be found by performing an exhaustive search over all possible user to BS assignments that satisfy the above mentioned constraints. However, exhaustive search complexity is exponential to the product of number of users, BSs, and RBs per base station. To solve the coordinated scheduling problem in linear time, this work proposed a low complexity heuristic. The sum rate of the proposed algorithm is compared with the optimal scheduling using exhaustive search. Simulation results are reported for a number of CRAN scenarios and suggest that the proposed heuristic algorithm performs near to optimal scheduling. Moreover, the proposed heuristic can be extended to coordinated scheduling multicloud RANs with various other practical channel scenarios.

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