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A Joint Power Allocation and User Association Based on Non-Cooperative Game Theory in an Heterogeneous Ultra-Dense Network

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ABSTRACT Driven by the increase of data traffic, a heterogeneous ultra-dense network (H-UDN) constitute one of the most promising techniques to support the 5G mobile system. Ultra-dense network (UDN) refers to the idea of densifying the cellular networks to reduce the distance between the access nodes and the user equipment (UE) to achieve the highest possible transmission rates and to enhance the quality of service (QoS). Despite these advantages, (H-UDN) introduces numerous challenges in terms of resource allocation. In this paper, we develop a joint power allocation and user association strategy in H-UDN using non-cooperative game theory. The proposed game is divided into two sub-games, the Backhaul Game is implemented between BS and RNs in the backhaul links and the Access Game is implemented between the BS/RNs and UEs in the access links. The leaders estimate the strategies of their followers to decide on their strategies. Therefore, our solution starts first by solving the users association in the access links to derive the optimal power strategies of the followers and then choosing their optimal power allocation strategies. Subsequently, the followers do the best response to the leaders' strategies. The simulation results show that our proposed algorithm can achieve the optimal power allocation and improve the performances of the system in term of throughput and UE rate compared to existing methods.

INDEX TERMS Heterogeneous ultra-dense network, non cooperative game theory, power allocation, QoS, relay, user association.

I. INTRODUCTION

With the increasing growth of data service and demand for a better quality of service, the next generation of mobile communication technologies will have a great demand for data traffic and QoS expectation. In order to meet these required demands, Ultra Dense Network (UDN) is considered as a key technology for 5G communication, by solving the problem of blind spots, achieving the goal of load balancing, improving the capacity and the performances of the system and reducing the distance between UEs and their serving station [1]. However, UDNs can also cause interference problems and difficulty to guarantee high-rate and low-delay [2]. Relaying can be a solution to these problems where one of the interesting features of RNs is the wireless backhaul, as it provides a simple way for throughput/coverage improvement [3]. Eventually, the interference mitigation strategies, joint backhaul and access resource management and backhaul capacity bottleneck solutions for H-UDN have become significantly challenging for operators especially when scaling up the network. Thus, joint resource allocation for the backhaul and access links is an extremely difficult problem [4]–[8]. The Problem of resource allocation in 5G UDN has been widely studied, but there are still open questions when dealing with the interference, bottleneck and backhaul/access links problems for resource allocation in an ultra-dense network. In [9], a hierarchical game based on the Stackelberg model with two sub-games is developed to address the resource allocation and bottleneck problems in heterogeneous relay networks. To provide fairness among users and alleviate the network backhaul load, the authors in [10], jointly optimize the power allocation at sources, the receive and transmit beamformers at relays, and the size of the cooperating relays. Simulation results show that the solution outperforms many existing

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multi-relay selection schemes and achieves performance very close to that of the exhaustive search scheme. A novel distributed algorithm that jointly tackles the coupled problems of user association, and TDD resource allocation, under cross interference constraints has been developed in [11]. Using optimization theory. It has been proven that the algorithm converges to the global optimum. Simulation results reveal promising qualitative and quantitative results, in terms of both user and network performance improvement. In [1], user association and power allocation in mm-Wave based UDNs is considered with load balance constraints, energy harvesting by base stations, user quality of service requirements, energy efficiency, and cross-tier interference limits. The results show that the load-balancing association and price control user association significantly improve the network utility and energy efficiency. Authors in [12], propose a downlink power allocation scheme for UDN based on local information by investigating non-cooperative game problems with a penalty and proposing a distributed optimal power control algorithm. In [13], the authors studied mean-field game framework for uplink power control in an ultra-dense millimeter wave network. The proposed mean-field game considers the time evolution of the mobile users orientations as well as the energy available in their batteries, under adaptive user association. The objective of each mobile user is then to find the optimal transmission power that maximizes its energy efficiency. Results have quantified the performance gains achieved when using the mean-field approach compared to the baseline in which the nodes transmit with maximum power. In [14], new approaches for jointly optimizing small cells-UE association and power allocation have been proposed in the context of 60 GHz millimeter-wave ultra-dense networks. the proposed methods have been targeted on maximizing the system EE subject to the QoS requirements of each UE. The numerical results demonstrated the computational low-complexity and effectiveness of the proposed algorithms. In [28], the authors analyze an in-band full-duplex access node that is serving mobile users while simultaneously connecting to a core network over a wireless backhaul link, utilizing the same frequency band for all communication tasks. The optimal transmit power allocation is solved for two reference scenarios: a purely half-duplex access node, and a relay-type full-duplex access node. The results indicate that a full-duplex capable access node is best suited for small cells.

The problem of joint resource allocation between backhaul and access links was addressed for dense small cell networks in [9], [15], [16] and for relaying systems in [17]–[19] proving that it's extremely difficult. However, most of these studies considered separately the resource allocation for the access and backhaul links and did not consider the throughput balance between the two links and the bottleneck problem and, have mainly focused on resource allocation of access or direct links since in cellular networks, BSs and RNs are subjected to different power constraints which can cause problem to power allocation especially for joint access and backhaul power allocation. This motivates us to address the joint power allocation for the backhaul and access links using non-cooperative game theory.

The main contributions of this paper are listed as follows:

- A power allocation based on non-cooperative game theory in a heterogeneous ultra-dense relay network is proposed in order to guarantee QoS requirements and throughput balance between the access and backhaul links while estimating the number of associated UEs.
- Formulation of the game: The game is divided into two sub-games, the backhaul game (BG) and the access game (AG). The players of the Backhaul Game are the leaders and the players of the Access Game are the followers. The Backhaul Game goes as follows; By estimating the user association in each station, the leader is able to estimate the possible optimal power allocation strategies of its followers in the BS-UEs or RN-UEs links. Then the leader chooses the optimal power allocation strategies for BS-RN links. The Access Game goes as follows; According to the leaders' strategies, the follower does the best response to its leader and the other followers.
- Extensive simulations are conducted to evaluate the performance of the proposed method. Experiment results validate the effectiveness of our solution in terms of throughput balance between the two links and the required minimum rate.

Remains of this paper is organized as follows. We describe the system model and formulate the problem in Section II. Section III elaborates on the proposed resource-allocation scheme based on non cooperative game theory. Section IV presents simulation results to validate our model and evaluate the performance of our game. Finally, Section V concludes this paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. SYSTEM MODEL

In Fig. 1, we consider an orthogonal frequency-division multiplexing (OFDM) heterogeneous ultra-dense network with one base station (BS) and multiple amplify-and-forward relay nodes (DF-RN) forming a multi-hop relay network overlaid on one macro-cell. We focus on downlink power allocation and user association. We assume that each relay is serving a set of UEs randomly distributed in the cell.

Both BS and RNs use OFDM modulation mode and the entire resources block are assumed orthogonal to each other to reduce the mutual interference between sub-channels (i.e., inter-channel interference (ICI)) and each resource block experiences flat fading to eliminate inter-symbol interference (ISI). Note that RB pairing in two-hop links is not applied here. As backhaul and access links are time-division multiplexed, the duration of the transmission is divided into two phases. Backhaul links are active in phase 1, whereas access and direct links are active in phase 2. For simplicity we do not introduce the duration $\theta = \{0, 1\}$ of the backhaul and

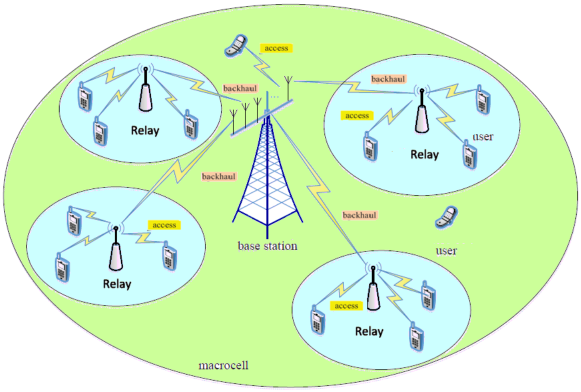

FIGURE 1. System model of multi-hop relay architecture based on 5G H-UDN.

access links where the end-to-end throughput can be given as $\min[\theta R_{backhaul}, (1-\theta)R_{access}]$.

Our proposed power allocation algorithm is designed with the assumption of a fixed bandwidth allocation to each sub-channel for all links. In other words, the total bandwidth is divided into a set of resource block (RB) where one RB of a transmitter is assigned to at most one receiver in any link, and each UE can be assigned a fixed number of RB. Let there be one BS o, $k = \{1 \dots K\}$ RNs and $m = \{1 \dots V_t\}$ UEs. Let V_0 be the set of UEs served by BS and V_k the set of UEs served by RNs. We can write the channel bandwidth of the backhaul links, the direct links and the access links are respectively denoted as follows B_{ok}, B_{om} and B_{km}.

We assume that one user can only be associated with one station, x_{km} is used to indicate the association variable between relay station k and UE m and x_{om} is used to indicate the association variable between BS o and UE m.

In this paper, we use the Friis transmission equation [27] to model the power gain of the different links. Let β_{ok}, β_{0m}, β_{km} be the power gain for the backhaul, direct and access links respectively expressed by:

$$\beta_{ok} = \frac{g_{ok}^{Tx} g_{ok}^{Rx} \tau^2}{16\pi^2 (\frac{d_{ok}}{d_0})^e},$$
$$\beta_{om} = \frac{g_{om}^{Tx} g_{om}^{Rx} \tau^2}{16\pi^2 (\frac{d_{om}}{d_0})^e},$$
$$\beta_{km} = \frac{g_{km}^{Tx} g_{km}^{Rx} \tau^2}{16\pi^2 (\frac{d_{km}}{d_0})^e}.$$

where g_{ok}^{Tx}, g_{om}^{Tx}, g_{km}^{Tx} are the transmit antenna gains, g_{ok}^{Rx}, g_{om}^{Rx}, g_{km}^{Rx} are the received antenna gains, τ is the wavelength, d_{ok}, d_{om}, d_{km} are the distance for the different links, d_0 is the far field reference distance, and e is the path-loss exponent.

In Phase 1, for the backhaul link, we assume that each RN obtains a full channel state information (CSI) regarding other backhaul links. The signal-to-interference-plus-noise ratio (SINR) of the received signal at RN is expressed by:

$$SINR_k = \frac{P_{ok}\beta_{ok}}{I_k + \sigma^2},$$

where P_{ok} is the transmission power from BS o to RN k, β_{ok} is the channel power gain between RN and BS, σ^2 the additional white Gaussian noise with distribution $CN(0, \sigma^2)$ and I_k is the interference caused by other adjacent cell as the RBs allocated for different RNs in a cell are orthogonal, intracell interference does not exist.

In Phase 2, for the access link, we assume that each UE obtains a full channel state information (CSI) regarding other access link with the same access point RN. The signal-to-interference-plus-noise ratio (SINR) of UE from RN k is expressed by:

$$SINR_m = \frac{P_{km}\beta_{km}}{I_k' + \sigma^2},$$

where P_{km} is the transmission power of RN to UE m, β_{km} is the channel power gain between UE and the serving station k, σ^2 the additional white Gaussian noise with distribution $CN(0, \sigma^2)$. I_k' is the interference caused by other stations and other adjacent cells to the mth UE. Interference in the same cell is considered negligible based on the fact that RBs are not reused and that the RBs are allocated in different orthogonal channel.

in Phase 2, for the direct link, we assume that each UE obtains a full channel state information (CSI) regarding other access link with the same access point BS. The signal-to-interference-plus-noise ratio (SINR) for UE from BS o is expressed by:

$$SINR_o = \frac{P_{om}\beta_{om}}{I_k' + \sigma^2}.$$

where P_{om} is the transmission power of BS, β_{om} is the channel power gain between the UE and BS.

According to Shannon equation, the throughput of the backhaul, direct and access link is given by respectively:

$$R_{ok} = B_{ok}\, log(1 + SINR_k),$$
$$R_{om} = B_{om}\, log(1 + SINR_o),$$
$$R_{km} = B_{km}\, log(1 + SINR_m).$$

where B_{ok}, B_{om} and B_{km} are respectively the bandwidths of the backhaul, the direct and the access links.

B. PROBLEM FORMULATION

The objective of our work is to maximize the total rate of UEs while guarantying their minimum required QoS. The optimization problem is therefore composed of two parts: the first one is the maximum rate of UEs of the direct links and the second one is the maximum rate of UEs limited by either the backhaul links or the access links. Thus the objective function can be formulated as:

$$\max \left\{ \sum_{m \in V_o} x_{om}\, R_{om} + \min\,(\sum_k R_{ok}, \sum_k \sum_{m \in V_k} x_{km} R_{km}) \right\} \quad (1)$$

$$\text{s.t. } C1: \sum_m x_{im} = n_i \quad \forall i = (0 \ldots k)$$
$$C2: 0 \le n_i \le V_t \quad \forall i = (0 \ldots k)$$
$$C3: \sum_i x_{im} = 1 \quad \forall m$$
$$C4: \sum_i x_{im} \quad R_{im} > R_{req} \quad \forall i = (0 \ldots K)$$
$$C5: P_{om} > 0, \quad P_{ok} > 0, \quad P_{km} > 0)$$
$$C6: \sum_k P_{ok} \le P^{BS}_{max}, \quad \sum_{m \in v_0} x_{om} P_{om} \le P^{BS}_{max},$$
$$\sum_{m \in v_k} x_{km} P_{km} \le P^{RN}_{max} \tag{2}$$

where C1 is the constraint that there are n_i users being served by station i (either BS or RNs), C2 specify the range of n_i, C3 guarantees that each user can be associated with only one station, C4 sets the minimum QoS requirement R_{req} to the associated UE m in term of data rate, C5 guarantees that all allocated powers are positives and C6 states that the sum of transmission power of different links needs to satisfy the limitation on their maximum power transmission and x1 and x2 are the user association for the direct and access link respectively.

This problem does not have a polynomial solution. Thus we propose to use non cooperative game theory for different links to solve it iteratively.

III. NON-COOPERATIVE GAME THEORY APPROACH

Most of the related works on resource allocation for relay networks does not consider explicitly the throughput balance between the backhaul and access links to improve the overall network throughput. Thus, we propose here a new formulation of our problem as a joint power allocation between the access and the backhaul links based on non cooperative game theory with two sub-games, a Backhaul Game implemented between the backhaul links (BS-RN) and an Access Game between the access links (BS/RN-UE). The players of the Backhaul Game are the leaders and those of the Access Game are the followers. In the Backhaul Game, the leaders estimate the strategies of its followers and then choose the optimal resource-allocation strategies for BS-RN links. Then, according to the strategies of the leaders, followers do the best responses to the leaders using the iteration method. In particular, player i ($i \in \{1, \ldots, K\}$) in the Access Game is the follower of player i (leader i) in the Backhaul Game.

A. THE GAME-THEORETIC FORMULATION

The framework of our proposed game is presented as follows; The players in BG are the leaders, they estimate the possible strategies of its followers and then choose the optimal power-allocation strategies for BS-RN links. The players in the AG are the followers. According to the strategies of the leaders, the followers chose the best responses to the leaders' decisions.

Let $\mathbb{B} = \{1 \ldots K\}$ the set of players in the Backhaul Game; let S_b be the set of power allocation strategies of player b and let U_b be the utility/payoff function of player b. The backhaul game denotes by Γ_1 is defined by:

$$\Gamma_1 = \{\mathbb{B}, \{S_b\}_{b \in B} \{U_b\}_{b \in B}\} \tag{3}$$

Let $\mathbb{A} = \{0, 1, \ldots K\}$ the set of players in the Access Game; S_a be the set of power allocation strategies of player a and let U_a be the utility/payoff function of player a. if $a \neq 0$ then the access node is RN and if $a = 0$ then the access node is BS. As each player a has multiple associated UEs, we denote P_a as a power allocation matrix. The access game Γ_2 is defined as:

$$\Gamma_2 = \{\mathbb{A}, \{S_a\}_{a \in \mathbb{A}}, \{U_a\}_{a \in \mathbb{A}}\} \tag{4}$$

Let R_b be the rate of player b in the Backhaul Game and R_a be the rate of player a in the Access Game. If $a = 0$ then $R_a = \sum_{m \in V_o} R_{om}$ represent the sum of all downlink rates of UEs that are connected to the BS. If $a \neq 0$ then $R_a = \sum_{m \in V_k} R_{km}$ represents the total downlink rates of UEs that are connected to RN k. To improve clarity, we call player b in Γ_1 leader b and player a in Γ_2 follower a.

We can define the best response of follower a as [20]:

$$P_a = argmax\ U_a(P_a, P_{-a}, P^*_b),$$

where P^*_b is the best strategy of power allocation of leader b and P_{-a} represent the power-allocation strategies of the followers except follower a. Let the equilibrium $P^* = (P^*_0, \ldots P^*_a, \ldots, P^*_K)$ of Γ_2 be

$$P^*_a = \mathbb{BR}(P^*_{-a}, P^*_b).$$

Similarly for the leader b, we define its best response as:

$$P_b = argmax \quad U_b(P_b, P_{-b}, P^*_a),$$

where P_{-b} represent the power-allocation strategies of the leaders except leader b and P^*_a is the strategy at equilibrium of follower a based on the strategy of Γ_1. The equilibrium $P^{'*} = (P^{'*}_1, \ldots P^*_b, \ldots, P^{'*}_K)$ of Γ_1 be:

$$P^*_b = \mathbb{BR}(P^*_{-b}, P^*_a).$$

Nash equilibrium is the most used solution to game theoretic problems. For our proposed game, we will use the pure strategy Nash equilibrium. Let R^{opt}_a and R^{opt}_b denote the maximum sum rate obtained by the optimal solution to Problem (1) for the access links and backhaul links respectively. Then we have the following lemma.

Lemma 1: $R^{opt}_a = R^{opt}_b$ needs to be satisfied in order to achieve the maximum throughput of the whole system where R^{opt}_a is the optimal rate of follower a and R^{opt}_b is the optimal rate of leader b.

Proof: If an arbitrary player violates one of the constraints in (2), then $\sum_{m \in V_o} x_{om} R_{om} + \min(\sum_k R_{ok}, \sum_k \sum_{m \in V_k} x_{km} R_{km})$ has no optimal solution when $R^{opt}_a = R^{opt}_b$. This means that the strategy profiles that cannot satisfy (2) will never be the optimal solution to the backhaul game and the access game. In other words, the optimal solution to the Backhaul Game must satisfy all the constraints (2) in order to have the optimal solution for the Access Game and to achieve the maximum throughput for the whole system [21].

According to lemma (1), $R_a^{opt} = R_b^{opt}$ needs to be satisfied in order to achieve the maximum throughput. Thus, we define the utility function of player b in the Backhaul game as

$$U_b = \exp(1 - \frac{R_a^{opt}}{R_b^{opt}}). \quad (5)$$

The leaders b of the backhaul game change power-allocation strategies to maximize their payoff. U_b is a convex function that converges to 1, when $R_a^{opt} = R_b^{opt}$, we obtain $U_b = 1$, and leader b can get the maximum payoff. In our game, the definition of the pure strategy Nash equilibrium is given as follows.

Definition 1: The strategy profile $P_b^* = \mathbb{BR}(P_{-b}^*, P_a^*)$ is said to be a pure strategy Nash equilibrium of the game [20], [21] if:

$$U_b(P_b^*, P_{-b}^*, P_a^*) \geq U_b(P_b, P_{-b}^*, P_a^*) \quad \forall P_b \in S_b \quad (6)$$

1) FEASIBILITY

We need to investigate the feasibility of the pure Nash equilibrium in case some of the power allocation strategies may not satisfy the constraints. The following theorem provides the required analysis.

Theorem 1: When $R_a^{opt} = R_b^{opt}$, then the best response is feasible and the pure strategy Nash equilibrium of Γ_1 is feasible.

Proof: We start the proof by assuming that $P_b \in S_b$ is a pure strategy NE of our game which violates at least one of the stated constraints (6). Assume that P_b^* is the best response of Γ_1 while the strategy of the other users is P_{-b}. Furthermore, we suppose that (P_b^*, P_{-b}, P_a^*) violates at least one of the stated constraints (6) [21].

If $R_a^{opt} = R_b^{opt}$ then $P_b^* \neq 0$, and having $U_b(P_b^*, P_{-b}, P_a^*) \notin [0, 1]$ and assuming that $\forall b \in \mathbb{B}$, $P_b > P_b^*$ then we can obtain:

$$U_b(P_b^*, P_{-b}, P_a^*) < U_b(P_b, P_{-b}, P_a^*) \quad \forall b \in \mathbb{B} \quad (7)$$

Obviously, (7) contradicts the assumption that P_b^* is the best response of Γ_1 for $b \in \mathbb{B}$, therefore, the Nash equilibrium must be feasible.

2) EXISTENCE

the existence of the pure strategy Nash equilibrium is investigated in the following theorem.

Theorem 2: when x_{am} is determined and R_a^{opt} is fixed, the pure Nash Equilibrium exists for this game.

Proof: the expression of transmission power P_{ok} is closed and bounded by P_{max}^{BS} therefore, the power-allocation strategy space of the Backhaul Game is a compact convex set [22].

Furthermore, the utility function U_b is a convex function of R_b. In this given condition, R_b is concave over P_b. Thus U_b is also concave in S_b [22]. In addition, U_b is obviously a continuous function, therefore, our game must have a pure Nash equilibrium point.

Similarly, We define the utility function of player a of the Access Game as the following:

$$U_a = \exp(1 - \frac{R_b^{opt}}{R_a^{opt}}) \quad \forall a, b = \{0 \ldots K\}. \quad (8)$$

B. BACKHAUL GAME SOLUTION

In the Backhaul Game, first, we need to estimate the optimal user association so that the leader considers the strategies of opponents and estimates the possible strategy of its followers. By estimating the best response of the follower, the leader will choose the strategy (the sub-game equilibrium P_b^*) with which it can obtain the maximum payoff. Thus, for the followers to obtain their maximum rate, they will choose the strategies such as $R_a = \max \sum_{a=0}^{K} \sum_{m \in V_t} R_{am}$, where P_{am} be the allocated power for the access link and x_{am} the user association between station a and UE m.

$$\max \sum_{a=0}^{k} \sum_{m \in V_t} x_{am} B_{am} \, log(1 + \frac{P_{am} \beta_{am}}{I'_k + \sigma^2}) \quad (9)$$

$$\begin{aligned} \text{S.t. } & C1: \sum\nolimits_a x_{am} = 1 \quad \forall m \\ & C2: \sum\nolimits_m x_{am} = n_a \quad \forall a \\ & C3: \sum\nolimits_a x_{am} \quad R_{am} > R_{req} \\ & C4: P_{om} > 0, \; P_{0k} > 0, \quad P_{km} > 0 \\ & C5: \sum_{m \in v_0} x_{om} P_{om} \leq P_{max}^{BS} \;\; if \;\; a = 0 \;\; ; \\ & \qquad \sum_{m \in v_k} x_{km} P_{km} \leq P_{max}^{RN} \;\; if \;\; a \neq 0 \end{aligned} \quad (10)$$

The Lagrangian function of the problem can be expressed as follows:

$$\begin{aligned} & L(\{x_{am}\}, \{P_{am}\}, \mu_a, \lambda_a, \nu_m) \\ & = \sum_{a=0}^{K} \sum_{m \in V_t} x_{am} B_{am} \, log(1 + \frac{P_{am} \beta_{am}}{I'_k + \sigma^2}) \\ & \quad + \sum_a \mu_a (n_a - \sum_m x_{am}) + \sum_a \lambda_a (P_{max} - \sum_m x_{am} P_{am}) \\ & \quad + \sum_m \nu_m (\sum_a x_{am} R_{am}) - R_{req}) \end{aligned} \quad (11)$$

where $\mu = [\mu_0 \ldots \mu_k]^T$ $\lambda = [\mu_0 \ldots \lambda_k]^T$ $\nu = [\nu_0 \ldots \nu_m]^T$ are the Lagrange multipliers used to relax the coupled constraint and for $a = 0$, We have $P_{am} = P_{om}$ and $P_{max} = P_{BS}^{max}$ and for $a \neq 0$ we have $P_{am} = P_{km}$ and $P_{max} = P_{RN}^{max}$.

We use the Lagrangian dual decomposition method to solve the relaxed problem (6) in order to estimate the user association strategies. Thus, We divide problem (5) into two independent sub-problems [22]. The Lagrangian dual function can be written as:

$$\min D(\mu, \lambda, \nu) = f_{X,P}(\mu, \lambda, \nu) + g_{n_a,P}(\mu, \lambda, \nu). \quad (12)$$

where

$$f_{X,P}(\mu, \lambda, \nu) = \begin{cases} \max \ (\sum_a \sum_{m\in V_t} x_{am} \quad B_{am}\ log(1+\frac{P_{am}\ \beta_{am}}{I_k' + \sigma^2}) \\ \quad -\sum_a \sum_m x_{am} \quad (\mu_a + \lambda_a P_{am} - \nu_m R_{am})) \\ s.t. \ \ \sum_a x_{am} \le 1 \quad \forall m \end{cases} \quad (13)$$

$$g_{n_a,P}(\mu, \lambda, \nu) = \begin{cases} \max \ \ (\sum_a (\mu_a n_a + \lambda_a P_{max}) - \sum_m \nu_m R_{req}) \\ s.t. \ \ n_a \le V_t \end{cases} \quad (14)$$

The partial derivative of sub-problem (9) can be expressed as:

$$\frac{\partial f_{X,P}}{\partial X_{am}} = B_{am}\ log(\frac{P_{am}\ \beta_{am}}{I_k' + \sigma^2}) - \mu_a - \lambda_a P_{am} + \nu_m R_{am} \quad (15)$$

The maximum of $\{x_{am}\}$ is defined as:

$$x_{am} = \begin{cases} 1, & if\ a = a^* \\ 0, & if\ a \ne a^* \end{cases} \quad (16)$$

where

$$a^* = \underset{a}{argmax}(B_{am}\ log(1+\frac{P_{am}\ \beta_{am}}{I_k' + \sigma^2}) - \mu_a - \lambda_a P_{am} + \nu_m R_{am}), \quad (17)$$

Equation (17) helps UEs to determine which station a (BS or RN) is capable of delivering the best service.

We can obtain n_a from the partial derivative of $\frac{\partial g_{n_a,P}}{\partial n_a}$:

$$n_a(t) = argmax\, \mu_a(t), \quad (18)$$

where n_a is used by the station a (BS or RN) to know how many UEs to associate with.

In the following, we use the subgardient method to update the Lagrange multipliers as follows [22]:

$$\mu_a(t+1) = [\mu_a(t) - \delta_1(t)(n_a - \sum_m x_{am}(t))]^+ \quad (19)$$

$$\nu_m(t+1) = [\nu_m(t) - \delta_2(t)(\sum_a x_{am}(t)\ R_{am} - R_{req})]^+ \quad (20)$$

$$\lambda_a(t+1) = [\lambda_a(t) - \delta_3(t)(P_{max} - \sum_m x_{am} P_{am}(t))]^+ \quad (21)$$

where $\delta_1(t)$, $\delta_2(t)$ and $\delta_3(t)$ are the step size and t is the turn of iteration. By updating the Lagrange multipliers via (19)-(21), the dual problem (12) will achieve the global optimum. In other words, when the multipliers converge reaching a solution that satisfies the constraints (10) at the end of the execution of the whole algorithm, we have solved the optimization problem for the UEs association and removed the UEs that do not satisfy the minimum required rate. Therefore, by minimizing the dual $D(\mu, \lambda, \nu)$, we will recover the optimal value max of equation (9).

After estimating the UEs association, the second step is to find the strategies of the power allocation of the followers assuming that UE m associated with the access node a. Therefore, under the joint association, x_{am} can be regarded now as a constant value of 1, $x_{am} = 1$ [23], thus, the following problem needs to be solved:

$$\max \ \sum_{a=0}^{K} \sum_{m\in V_t} \quad x_{am} \ \ B_{am}\ log(1+\frac{P_{am}\ \beta_{am}}{I_k' + \sigma^2})$$
$$s.t. \ \ \sum_m P_{am} \le P_{max}. \quad (22)$$

where

$$\begin{cases} \sum_{m\in v_o} P_{om} \le P_{max}^{BS} & if\ a = 0 \\ \sum_{m\in v_k} P_{km} \le P_{max}^{RN} & if\ a \ne 0 \end{cases}$$

The Lagrangian of (19) is written as:

$$L = (\sum_{a=0}^{K} \sum_{m\in V_t} x_{am}\ B_{am}\ log(1+\frac{P_{am}\ \beta_{am}}{I_k' + \sigma^2}) + \sum_a \alpha_a (P_{max} - \sum_m P_{am})$$

The Partial derivative of (19) is given by:

$$\frac{\partial L}{\partial P_{am}} = \frac{x_{am}\ B_{am}\ \beta_{am}}{(I_k' + \sigma^2) + P_{am}\ \beta_{am}} - \alpha_a \quad (23)$$

At this stage, if the strategies of other players are determined, the interference I_k' can be considered as determined. Thus, after applying Karush-Kuhn-Tucker (KKT) conditions, we have $\frac{\partial L}{\partial P_{am}} = 0$. The optimal power allocation of player a in the access link for each m is expressed by:

$$P_{am}^{opt*} = [\frac{x_{am}\ B_{am}}{\alpha_a} - \frac{1}{c_m}]^+ \quad (24)$$

where $c_m = \frac{\beta_{am}}{I_k' + \sigma^2}$ and $x^+ = max(x, 0)$. We update α_a using the subgardient method as follows:

$$\alpha_a(t+1) = [\alpha_a(t) - \delta_4(t)(P_{max} - \sum_m P_{am}(t))]^+ \quad (25)$$

Until $|\alpha_a(t+1) - \alpha_a(t)| < \epsilon$ where δ_4 is the step size. Once α_a converge, P_{am}^{*opt} is defined. Thus, it is possible to calculate the optimal estimated throughput of the access links as R_a^{opt} follows:

$$R_a^{opt} = \sum_{m\in V_k} x_{am}\ B_{am}\ log(1+\frac{P_{am}^{*opt}\ \ \beta_{am}}{I_k' + \sigma^2}). \quad (26)$$

In summary, first, we assessed the optimal user association so that the leader can estimate the optimal power strategy of its follower. Based on these strategies, we need to consider the optimization of the backhaul links (BS-RN):

$$\max \ \ \sum_b R_b \quad (27)$$
$$\text{s.t.} \ \ \sum_k P_{ok} \le P_{max}^{BS}$$
$$P_{ok} > 0 \quad \forall k \quad (28)$$

The Lagrangian function is written as:

$$L = \sum_k B_{ok}\ log(1+\frac{P_{ok}\ \beta_{ok}}{I_k + \sigma^2}) + \eta(P_{max}^{BS} - \sum_k P_{ok}) \quad (29)$$

After applying Karush-Kuhn-Tucker (KKT) conditions, we have $\frac{\partial L}{\partial P_{ok}} = 0$, the optimal power allocation defined as:

$$P_{ok}^{*opt} = [\frac{B_{ok}}{\eta} - \frac{1}{C_k}]^{+} \quad (30)$$

where $C_k = \frac{\beta_{ok}}{I_k+\sigma^2}$ and η is the Lagrange multiplier obtained by $P_{max}^{BS} - \sum_k P_{ok} = 0$. Thus, the optimal rate of the backhaul link of RN k is expressed as

$$R_b^{opt} = B_{ok} log(1 + \frac{P_{ok}^{*opt}\ \beta_{ok}}{I_k + \sigma^2}). \quad (31)$$

Now we can summarize the backhaul game as follows, the UE can determine the station with the best service based on the judgment criterion in (17) then the leaders estimate the possible optimal throughput of the access links R_a^{opt} and then based on these strategies, the BS allocate the optimal power allocation to RN until reaching the Nash equilibrium where R_b^{opt} needs to be equal to the maximum throughput R_a^{opt} so that the allocated power of RN k $P_b^* = \{P_{ok}^*\}$ at the equilibrium can be obtained.

C. ACCESS GAME ALGORITHM

Having obtained the power allocation strategy of the leaders b at the equilibrium P_{ok}^*, follower a needs to choose the best responses to the strategies of the leader.

We can use an iteration method to solve the power optimization problem under the constraint $R_a^{opt} = R_b^{opt}$ and the power P_{am}^{opt*} is updated as follows:

$$P_{am}(t+1) = P_{am}(t) + \delta_5(t)\ \Delta P. \quad (32)$$

where δ_5 is the step size and Δp is given by

$$\Delta P = \frac{R_b - R_a}{R_b} \quad (33)$$

We summarize the Access Game as follows, when R_b^{opt} is determined, the follower a does the best response to the leader b and the other followers. we allocate the power to follower a using (32) until it reaches convergence where the final strategy profile P_{am}^* is the equilibrium of Γ_2.

D. ALGORITHM IMPLEMENTATION

In this section, we present the implementation of our non-cooperative game theory solution to solve user association and power allocation. The proposed iterative Algorithm 1 will guarantee convergence by using the gradient method. In Algorithm 1, we perform the Backhaul Game and the Access Game in sequence. First, we suppose that the optimal solution to the problem (1) requires N_{max} iterations to converge. All UEs at each iteration will receive the required number of associated UEs of all the stations by choosing one of the stations to associate with, which can guarantee their minimum required rates (17). Then the leaders estimate the maximum rate R_a^{opt} (26) of the followers obtained by the optimal solution of (12) and then chooses the optimal power allocation strategies (where R_b^{opt} can be close or equal to R_a^{opt} and the sub-game equilibrium $P_{ok}^* = P_b^*$ is obtained.

Algorithm 1 User Association and Power Allocation Using Non Cooperative Game Theory

Initialization : $N_{max}, I_k, I_k', I_k'', P_{ok} = P_{am} = 2, C_m, C_k$
Initialization : Set the Lagrange multipliers μ_a, λ_a, ν_m and user association x_{am} to zero and α_a, η to one
set $n = 0$
repeat
  set $n = 0$
  repeat
    # Backhaul Game
    # user association
    for $a =$ 0 *to* K **do**
      for $m =$ 1 *to* V_t **do**
        Calculate a^* *according to* (17);
        Use a^* *to update* x_{am} *according to* (16);
        Update μ_a *according to* (19);
        Update ν_m *according to* (20);
        Update λ_a *according to* (21);
      end for
    end for
    # Estimated Optimal Access power allocation
    for $a =$ 0 *to* K **do**
      for $m =$ 1 *to* V_t **do**
        Update p_{am}^{*opt} *according to* (24);
        Update α_a *according to* (25);
        Calculate R_a^{opt} *according to* (26);
      end for
    end for
  until *convergence or* $n = N_{max}$
  # Optimal Backhaul power allocation
  set $n = 0$
  repeat
    for $k =$ 1 *to* K **do**
      Update p_{ok}^{*opt} *according to* (30);
      use P_{ok}^* *to Calculate* R_b^{opt} *according to* (31);
    end for
  until $R_b^{opt} = R_a^{opt}$ *or* $n = N_{max}$
  # Access Game power allocation
  set $n = 0$
  repeat
    for $a =$ 0 *to* K **do**
      for $m =$ 0 *to* V_t **do**
        Update ΔP *according to* (33);
        Update P_{am} *according to* (32);
      end for
    end for
    use P_{am}^* *to Calculate* R_a
  until $R_a^{opt} = R_b^{opt}$ *or* $n = N_{max}$
until $R_a^{opt} = R_b^{opt}$ *or* $n = N_{max}$

In the Access Game, Each follower do the best response to its leader and the other followers. The sub-game equilibrium $P_{am}^* = P_a^*$ of the Access game can be obtained in several iterations as the power is updated according to (32).

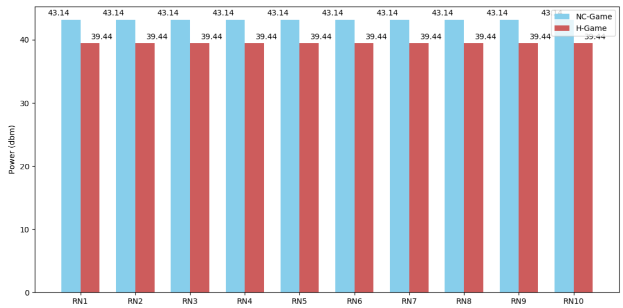

FIGURE 2. Allocated power in the Backhaul Game.

Hence, the strategy profile $(P_{ok}^{*}, \ P_{am}^{*})$ $(\forall K, \ \forall m)$ can be deemed as the final equilibrium of our game.

IV. PERFORMANCE EVALUATION

Our objective is to maximize the total rate of UEs in the cell while guaranteeing the QoS requirements, reducing the interference and solving the bottleneck and user association problem. In this section, we use simulation experiments to validate the effectiveness of the proposed power allocation and user association algorithm based on non-cooperative game theory. The metrics we use for performance evaluation include the allocated power and the throughput of the backhaul and access links respectively, compared to the hierarchical game [9], [24]–[26] and the UE rate compared to the non-linear for the whole system.

A. SIMULATION SETTING

In Fig. 1, we consider an ultra-dense network where all users are distributed within one macro-cell with ten fixed RNs. We consider that all the users have the same QoS requirements. The proposed joint power allocation and user association based on non-cooperative game theory (NC-Game) are compared to Hierarchical game theory (H-Game) for the resource allocation in cellular networks with relays for this we take the example of [9], [24]–[26]. With a fixed number of assigned UE in each cell, in this proposed hierarchical game, a Backhaul Level Game (BLG) and an Access Level Game (ALG) are implemented in sequence. In the BLG, the water-filling algorithm is used to obtain the maximum throughput for the backhaul links. In the ALG, each follower updates its strategy until an NE is obtained. The main difference of H-Game and our game is that H-Game does not consider the impact of the access links when performing resource allocation for backhaul links or the impact of dynamic user association. We denote that we do not consider the UE position or location in both algorithms [29], we only consider the distance between the station and the UE. Thus, the simulation parameters are based on the Third-Generation Partnership Project (3GPP) and listed in Table 1.

B. NUMERICAL RESULTS AND DISCUSSIONS

Fig. 2 shows the allocated power of each RN in the backhaul links. The BS allocates 43.14 dBm compared to 39.44 dBm

TABLE 1. Simulation parameters.

Parameter	symbol	value
Cell radius		1000 m
Max BS Power	P_{max}^{BS}	46 dBm
Max RN Power	P_{max}^{RN}	43 dBm
Wavelength	τ^2	5 mm
Path-loss Exponent	e	[2,6]
Transmit antenna gain	$g_{0k}^{Tx}, g_{om}^{Tx}, g_{km}^{Tx}$	1
Received antenna gain	$g_{0k}^{Rx}, g_{om}^{Rx}, g_{km}^{Rx}$	1
Terminal Noise Density	σ^2	-110 dBm/Hz
Bandwidth	B_{ok} B_{am}	1 MHz 909.090 kHz
Number of RN	K	10
Total number of users	Vt	180
Required rate	R_{req}	1 Mbps
Distance	d_{am}	[2, 100] m
far field reference distance	d_0	1 m
Link		Downlink

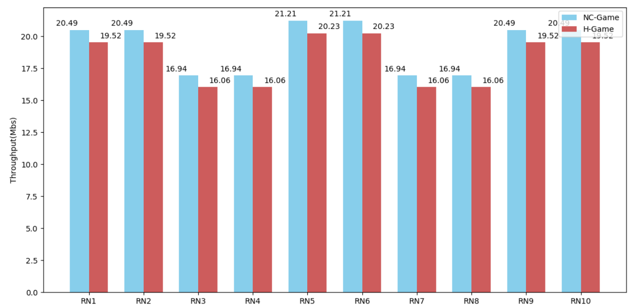

FIGURE 3. Throughput in the Backhaul Game.

in the H-Game. This can be explained by the increase in the interference, the bottleneck of access links and the densifying nature of our network in one hand. On the other hand, all the stations use the maximum power in order to achieve the NE (Throughput balance between the access links and the backhaul links) related to the estimated strategies of the followers and estimated number of associated UEs for the RN-UEs links in the Backhaul Game. Therefore, the RNs in the cells use more transmitted power.

In Fig. 3 the throughput is obtained by the power allocation of the backhaul game. In NC-Game the maximum throughput is achieved after having the estimated number of associated users and the estimated throughput of the RN-UEs links, however, in the H-Game the throughput is achieved after having only the estimated throughput of the RN-UEs links. We can see that the throughput of the NC-game is higher than the H-game. The throughput of RN1 for a distance of 42.42 m is 20.49 Mbps compared to 19.52 Mbps in the H-Game, for a distance of 45.27 m, the throughput of RN5 is 21.21 Mbps compared to 20.23 Mbps in the H-game and for a distance of 14.14 m, the throughput of RN8 is 16.94 Mbps compared to 16.06 Mbps in the H-game. Thus, as we can see the estimation of the strategies of the followers and of the associated UEs and the distance between the BS and the RN plays a role in the given throughput by the BS for the backhaul links.

In order to satisfy the Nash Equilibrium in our NC-Game $R_a^{opt} = R_b^{opt}$ and the users' required QoS, $R_{req} = 1 \ Mbps$,

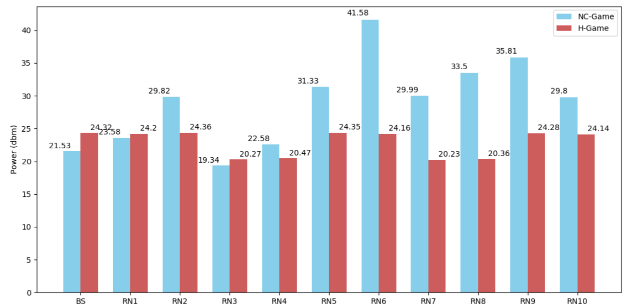

FIGURE 4. Allocated power in the Access Game.

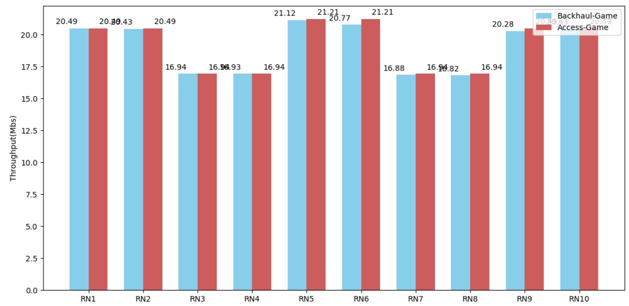

FIGURE 6. Throughput of the Backhaul Game vs. throughput of the Access Game.

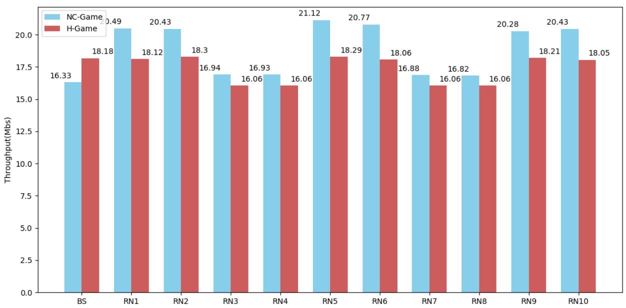

FIGURE 5. Throughput in the Access Game.

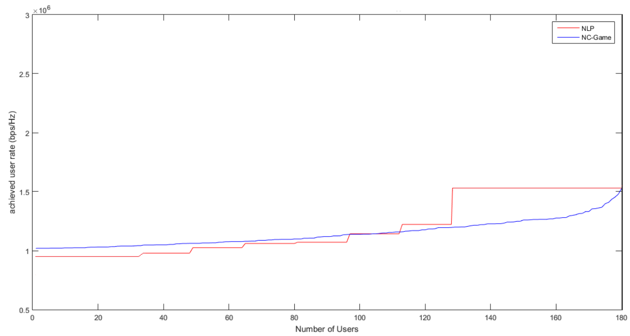

FIGURE 7. Number of UEs vs. the achieved throughput.

the iteration method uses equation (32) to update the power as shown in Fig. 4. In the NC-Game, the power allocation in the access links is the best response of the power allocation in the Backhaul Game, thus, we have the power consumption of each link depends on the associated UEs and the optimal rate of the backhaul Game. RN1 allocates an average of 23.58 dBm compared to 24.02 dBm in the H-Game, RN5 allocates an average of 31.33 dBm compared to 24.35 dBm in the H-Game and RN10 allocates an average of 29.8 dBm compared to 24.14 dBm in the H-Game. Due to the bottleneck problem and in order to balance the throughput of the two sub-games to satisfy the Nash Equilibrium of the NC-Game and having a dynamic number of associated UEs, our game uses more power than the hierarchical game (H-game) which is understandable.

Fig. 5 shows the throughput of the Access Game. We can see That there is a difference of ϵ between the Access Game and the Backhaul Game which means that the Nash Equilibrium of the proposed algorithm is satisfied and the throughput balance between the links is achieved, which is the purpose of our game. Moreover, the throughput of the Access Game satisfies the required QoS. Having the throughput of the direct link 16.33 Mbps for 16 associated UEs compared to 18.18 Mbps in the H-Game for 17 UEs, the throughput of RN1 is 20.48 Mbps for 20 associated UEs compared to 18.12 Mbps in the H-Game for 17 UEs and the throughput of RN5 is given as 21.12 Mbps compared to 18.23 Mbps for 17 associated UEs and finally the throughput of RN10 is 20.43 Mbps compared to 18.05 Mbps for 17 associated UEs. In our proposed algorithm, all UEs in the system can find the optimal station (either BS or RN) that provides the best services for them and the minimum required rate while balancing the links' throughput and maximizing the total rate of UEs. Compared to the H-Game, our proposed game provides better performance and higher throughput.

Fig.6 shows the throughput of the Backhaul Game and the Access Game respectively. We can see that the Throughput of the access links is almost the same as the backhaul link compared to the H-game where we can see there is a difference between the two results in different stations. Thus, even though NC-Game consumes more power in the access Game than the H-Game, it provides better performance and higher throughput and achieves the objective of our work in terms of throughput balancing and data rate improving on one hand. On the other hand, in our approach, the UEs are associated dynamically based on the best station that provides the best service for them compared to the hierarchical game that fixes the number of assigned UEs in the cell and calculates their Throughput.

Fig. 7 shows the UE rate of all the UEs in the system. We use non-linear programming to investigate the overall performance of the whole system compared to our approach that uses two staged games as a whole. We can see that it is difficult to maintain the minimum required rate for all the UEs and the throughput of the two hop links degrade from one to another. Thus, as the result of the overall system performance without considering the throughput balancing between the backhaul and the access links is lower than the NC-Game for some UEs and higher for others, proving that considering throughput balancing and solving the bottleneck problem gives a better rate to all the associated users in the cell while satisfying the minimum required rate.

We compared our proposed algorithm NC-Game to the Hierarchical game, the simulation results show that our approach gives better performance results and higher total rate for all the UEs while guaranteeing the minimum required rate. In addition, we compared NC-Game with non-linear programming in order to prove the effectiveness of our approach by having two sub-games compared with one game for the whole system.

V. CONCLUSIONS

In this paper, we have considered a joint user association and power allocation using non-cooperative game theory under QoS constraints in order to maximize the total rate of UEs in the cell of different links while reducing interference and guaranteeing QoS requirements. In order to achieve this objective we divided the problem into two sub-games, the first game is the Backhaul Game in which by estimating the optimal strategies for the followers, the leaders choose their optimal power allocation strategies and the second one is the Access Game where the followers do the best response to its leaders.

The simulation results show that our approach outperforms the Hierarchical game. The numerical results demonstrate the effectiveness of our algorithm by guaranteeing a dynamic UE association, a higher total rate for all the UEs and throughput balance between the access and backhaul links. For future works, we will study the energy efficiency and bandwidth allocation in a Heterogeneous ultra-dense network while including the UE location in the cell by dividing them into different groups according to their moving speeds.

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