Coalition Game for User Association and Bandwidth Allocation in Ultra-Dense mmWave Networks

(Invited Paper)

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***Abstract*—In future layered 5G wireless networks, a large number of millimeter-wave (mmWave) small cells will be covered by a microwave macrocell, where radio access links to a small cell and the backhaul link to its macrocell share a common mmWave bandwidth, which is called wireless self-backhauling. One of the major challenges in self-backhauling ultra-dense networks (UDNs) is the optimization of user association and resource allocation between the radio access links and backhaul links, which is essential to improve the network performance. This paper proposes a coalition game based joint user association and bandwidth allocation algorithm for ultra-dense mmWave networks (UDMNs), in which users form a set of coalitions by playing coalition games to maximize network sum rate and make the downlink traffic of small cells in current cell association period be accommodated by their wireless backhaul. Simulation results show that, the proposed scheme improves the sum rate significantly compared to the traditional minimum-distance based user association scheme, and approximates the performance of immune optimization algorithm (IOA) in terms of sum rate and has much lower computational complexity.**

***Index Terms*—ultra-dense networks (UDNs), user association, millimeter-wave (mmWave), wireless self-backhauling.**

I. Introduction

To meet the increasing demand on mobile data traffic, it is essential for 5G wireless networks to boost network throughput by more than 1000 times beyond 2020 [1]. Millimeter-wave (mmWave) communication which is emerging as a key technology for enabling extremely high data rate for next generation cellular systems, is an important solution to address the above requirement thanks to the large bandwidths available at mmWave bands [2]. Nevertheless, the challenges in mmWave communications due to the very high frequency of mmWave bands, such as severe path-loss, deafness, and blockage, limit the coverage in practical application scenarios [3], [4]. Fortunately, the ultra-dense deployment of small cells increases the coverage per square kilometer and is also considered as another important technology for providing multi-Gbps data rates in future cellular networks [5]. With the ultra-dense deployment of mmWave small base stations (SBSs), the access distance is reduced and the choice of serving SBSs for each user equipment (UE) is enriched, which are quite useful for alleviating the propagation loss and blockages [6]. Therefore, ultra-dense networks (UDNs) together with mmWave communications are envisioned to provide orders of magnitude capacity improvement for future wireless networks.

Recently, several research work has been done on ultra-dense mmWave networks (UDMNs) [6]-[11]. In [6], the gain of ultra-densification for mmWave communications was investigated from a network-level perspective taking into account high path loss and blockages. In [7], the architecture and radio resource coordination among multiple nodes for ultra-dense networks in mmWave frequencies were investigated. In [8], resource allocation for mmWave-μWave networks was studied where cell association is decoupled in the uplink for mmWave UEs. The advantages and challenges for mmWave fronthaul technologies in ultra dense cloud small cell network were surveyed in [9]. In [10], joint user association and power allocation in mmWave UDNs were studied considering energy harvesting by base stations, load balance constraints, energy efficiency, user quality of service requirements, and cross-tier interference limits. In [11], a joint user association and resource allocation scheme was developed to maximize the sum rate of all UEs for self-backhaul ultra-dense mmWave networks. However, most of these works did not consider ultra-dense mmWave networks with wireless self-backhauling. Only the study in [11] considered both ultra-dense mmWave networks and wireless self-backhauling, but the computational complexity of its solution is too high to be feasible in practice. Therefore, this paper aims to address the optimization of joint user association and bandwidth allocation for wireless self-backhauling UDMNs.

Wireless self-backhauling, in which the same radio spectrum is used for both access and backhaul transport [11], [12], is very crucial for future UDMNs. The reason is that it is infeasible for a large number of mmWave SBSs to connect to macro base stations (MBSs) by fiber links due to the expensive cost caused by network densification, where the MBSs act as anchored BSs (A-BSs) connected to the core network by fiber links, and the mmWave SBSs need the assistance of the A-BSs to receive (forward) the traffic from (to) the core network. However, when the frequency-division scheme is adopted in UDMNs, one of the major obstacles is the balance of resources between the radio access links and the backhaul link for each small cell, which is essential to improve the network sum rate performance but challenging to be addressed. The reasons are twofold. On the one hand, to avoid frequency band overlap between access and backhaul links, the bandwidth allocation ratios of all small cells should be the same. Moreover, all the downlink traffic of the associated UEs of any small cell in current cell association period should be accommodated by its wireless backhaul, which limits the backhaul bandwidth at the maximum backhaul bandwidth of all small cells. On the other hand, the constraints on the number of beams supported by each SBS due to the limited radio frequency (RF) chains and the large amount of UEs and SBSs in dense mmWave

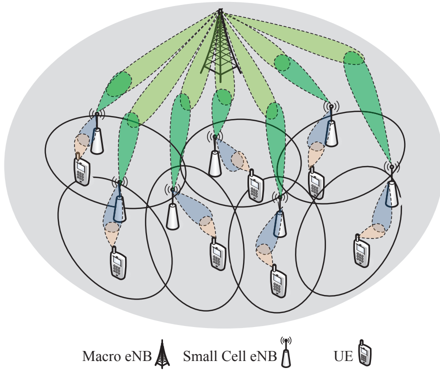

Fig. 1. UDNs with wireless mmWave self-backhauling.

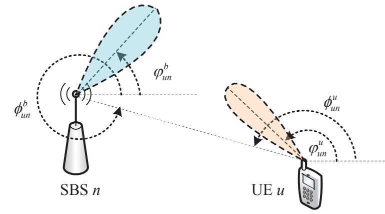

Fig. 2. Sectored antenna model.

networks increase the complexity of finding the solution, and thus a lower complexity algorithm is desired. Therefore, to maximize the sum rate of all small cells, user association and bandwidth allocation should be jointly considered carefully. In this paper, to deal with the above challenges, a coalition game based joint user association and bandwidth allocation scheme is proposed, which aims at maximizing the sum rate of all small cells.

The reminder of this paper is organized as follows. In Section II, we introduce the system model and problem formulation. The coalition formation algorithm for joint user association and bandwidth allocation in UDMNs is proposed in Section III. Section IV provides the simulation results. Finally, concludes are drawn in Section V.

II. System Model and Problem Formulation

We consider a downlink cellular network consisting of a macro cell and *N* small cells as shown in Fig. 1, where *U* UEs are randomly located in the *N* small cells. The backhaul traffic of each small cell is transmitted from the MBS by mmWave communication links while the MBS is connected to the core network by fiber. The unified access and backhaul network with a control-plane/user-plane (C-plane/U-plane) s-plit architecture is considered, where the C-plane and U-plane are managed by the MBS through low frequency bands and by SBSs through mmWave bands, respectively. For clarity, the C-plane is not shown in Fig. 1. For analytical tractability, the sectored antenna model is considered as shown in Fig. 2, which was widely used in [13]-[15] for system level performance analysis and radio resource allocation. Let θ_u^u and θ_n^b denote the operating beamwidths of the UE *u* and the SBS *n*, respectively. Let φ_{un}^b and φ_{un}^u be the boresight angle of the SBS *n* to the UE *u* and the boresight angle of the UE *u* to the SBS *n* relative to the positive *x*-axis, respectively. ϕ_{un}^b denotes the angle between the positive x-axis and the direction in which SBS *n* sees UE *u*, and ϕ_{un}^u is the angle between the positive *x*-axis and the direction in which UE *u* sees SBS *n*. We denote by p_n the transmission power spectrum density of SBS *n*, by N_0 the background noise power spectrum density, and by $g_{u,n}^c$ the channel gain between SBS *n* and UE *u*, capturing both path-loss and shadowing effects. Let $g_{u,n}^b$ and $g_{u,n}^u$ be the transmission and reception directivity gain between SBS *n* and UE *u* respectively, which can be given by

$$g_{u,n}^b(\theta_n^b,\varphi_{un}^b,\varphi_{un}^b)=\begin{cases} z, \text{if}\, \dfrac{\theta_n^b}{2}\le|\varphi_{un}^b-\phi_{un}^b|\le 2\pi-\dfrac{\theta_n^b}{2} \\ \dfrac{2\pi-(2\pi-\theta_n^b)z}{\theta_n^b}, \text{otherwise} \end{cases} \tag{1}$$

and

$$g_{u,n}^u(\theta_u^u,\varphi_{un}^u,\varphi_{un}^u)=\begin{cases} z, \text{if}\, \dfrac{\theta_u^u}{2}\le|\varphi_{un}^u-\phi_{un}^u|\le 2\pi-\dfrac{\theta_u^u}{2} \\ \dfrac{2\pi-(2\pi-\theta_u^u)z}{\theta_u^u}, \text{otherwise} \end{cases} \tag{2}$$

where $0 \le z < 1$ denotes the gain in the side lobe, with $z \ll 1$ for narrow beams. The signal to interference and noise ratio (SINR) experienced by UE *u* associated with SBS *n* can be expressed as

$$\mathrm{SINR}_{u,n}=\frac{p_n g_{u,n}^b g_{u,n}^c g_{u,n}^u}{\sum\limits_{k\in\Omega\backslash u}\sum\limits_{n\in\mathcal{N}} x_{k,n} p_n \bar{g}_{u,n}^b g_{u,n}^c \bar{g}_{u,n}^u + N_0}, \tag{3}$$

where Ω is the set of UEs. It is worth noting that $\bar{g}_{u,n}^b$ and $\bar{g}_{u,n}^u$ which can be also calculated as shown in Fig. 2 represent the transmission directivity gain between the beam to UE *k* and UE *u*, and the reception directivity gain between the SBS n and the beam of UE *u*, respectively.

Assume that the whole mmWave bandwidth is $B = B^{bh} + B^{ra}$, where B^{bh} and B^{ra} represent the backhaul bandwidth and radio access bandwidth, respectively. Since we mainly focus on the data transmissions in mmWave band, the achievable data rate of the backhaul link for the *n*-th small cell can be given by

$$T_n^{bh}=B^{bh}R_n^{bh}=B^{bh}\log_2(1+\mathrm{SINR}_n), \tag{4}$$

and the achievable data rate of radio access links for the *n*-th small cell is

$$T_n^{ra}=B^{ra}R_n^{ra}=(B-B^{bh})\sum_{u\in A_n}x_{u,n}\log_2(1+\mathrm{SINR}_{u,n}), \tag{5}$$

where SINR_n is the SINR between SBS *n* and the MBS, which can be also calculated similar to formula (3), A_n is the set of the UEs associated to SBS *n*. $x_{u,n}$ is the binary association variable, i.e. $x_{u,n}=1$ if UE *u* is associated to the SBS *n* and uses the optimal beam between them to transmit data, otherwise $x_{u,n}=0$.

Considering that non-line-of-sight (NLOS) transmissions suffer from significant attenuation, we mainly focus on the line-of sight (LOS) transmissions. We assume that the optimal beams between any SBSs and any UEs have been determined in advance. Similar to [16], we assume network topology information can be obtained in sufficient precision. To maximize the sum rate of all small cells, the optimization problem jointly considering user association and bandwidth allocation can be formulated as

$$
\begin{aligned}
&\max_{\mathbf{x},B^{bh}} \sum_{n=1}^{N} T_n^{ra} && (6)\\
&\text{s.t.} \quad C1: B^{bh} + B^{bh} = B, \\
&\qquad C2: \textstyle\sum_{n=1}^{N} x_{u,n} = 1, && \forall u \\
&\qquad C3: x_{u,n} = \{0,1\}, && \forall u, n \\
&\qquad C4: \textstyle\sum_{u=1}^{U} x_{u,n} \le N_n^{\mathrm{RF}}, && \forall n \\
&\qquad C5: T_n^{ra} \le T_n^{bh}, && \forall n
\end{aligned}
$$

where constraint C1 represents the fraction constraint of bandwidth allocated for wireless backhauling; constraints C2 and C3 are the user association constraints, and C3 means one UE can be only associated to one SBS at most; Constraint C4 represents the number of UEs associated to each SBS should not exceed N_n^{RF}, where N_n^{RF} is the number of RF chains of SBS *n*; Constraint C5 is imposed to guarantee that all the downlink traffic of the associated UEs of any small cell *n* in current cell association period can be accommodated by its wireless backhaul.

III. Proposed Joint User Association and Bandwidth Allocation Scheme

Since the problem in (6) is a mixed integer, non-linear optimization problem, finding its optimal solution is generally NP-hard. Fortunately, coalition game provides an effective way to solve this optimization problem [17]-[20]. Thus, we propose a coalition game based joint user association and bandwidth allocation algorithm to solve the optimization problem in (6). The considered problem can be formulated as a coalition formation game $\mathcal{G} = \{\mathcal{U}, \mathcal{X}, \mathcal{R}\}$, where the set of UEs $\mathcal{U}$ is the player set, the binary association variables set $\mathcal{X}$ is the strategy space, and $\mathcal{R}$ is the payoff set. In the proposed coalition game, to maximize the sum rate of all small cells and make the downlink traffic of small cells in current cell association period be accommodated by their wireless backhaul, the players form coalitions to associate to SBSs. Since there are *N* small cells in the network, *U* UEs will form *N* coalitions. The coalition structure can be denoted by $\mathcal{A} = \{A_1, A_2, ..., A_N\}$, where $A_n \in \mathcal{A}$ is the coalition formed by the players, holding the condition of $A_n \cap A_{n'} = \emptyset, \forall n \neq n'$, and $\cup_{n=1}^{N} A_n = \mathcal{U}$. To quantify the coalitional value of a coalition, we define its payoff as

$$R(A_n, \mathcal{A}) = T_n^{ra}, \forall n \in \mathcal{N}. \tag{7}$$

Following [19], the payoff of any player $u \in \mathcal{A}$ is defined as the average payoff under the partition of the network $\mathcal{A}$, which can be given as,

$$R_u(A_n, \mathcal{A}) = \frac{\sum_n R(A_n, \mathcal{A})}{|\mathcal{U}|}, \forall u \in A_n, A_n \in \mathcal{A}, \tag{8}$$

where $|\mathcal{U}|$ denotes the number of players.

For any partition $\mathcal{A} = \{A_1, A_2, ..., A_N\}$, the value for the game can be given by

$$v(\mathcal{A}) = \sum_{n \in \mathcal{N}} R(A_n, \mathcal{A}) = \sum_{n \in \mathcal{N}} \sum_{u \in A_n} R_u(A_n, \mathcal{A}), \tag{9}$$

Given the preference order, every player can make a decision on whether it should perform the following switch operation. Therefore, we need to define the preference order $\triangleright_u$ for any UE $u \in \mathcal{U}$.

Definition 1: For any UE $u \in \mathcal{U}$, the preference order $\triangleright_u$ is defined as a complete, transitive, and reflexive binary relation over the set of all partitions that UE *u* can possibly form.

For any UE *u*, given two partitions $\mathcal{A}$ and $\mathcal{A}'$ of UEs $\mathcal{U}$, $\mathcal{A} \triangleright_u \mathcal{A}'$ means that UE *u* prefers becoming a member of a coalition to form partition $\mathcal{A}$ over becoming a member of another coalition to form partition $\mathcal{A}'$. The operation that decides the preference $\mathcal{A} \triangleright_u \mathcal{A}'$ can be defined as follows:

$$\mathcal{A} \triangleright_u \mathcal{A}' \Leftrightarrow \begin{cases} v(\mathcal{A}) > v(\mathcal{A}') \\ T_n^{ra} \le T_n^{bh}, & \forall n \end{cases} \tag{10}$$

This definition indicates the UE *u* prefers performing the switch operation only if such a switch yields a larger game value v and all the backhaul load constraints of small cells are satisfied. According to the preference order, players can perform switch operations based on the switch rule defined as follows.

Definition 2 (Switch Rule): Given a partition $\mathcal{A}' = \{A_1, A_2, ..., A_N\}$ of UEs $\mathcal{U}$, UE *u* decides to leave its current coalition $A_{n'} \in \mathcal{A}'$, and join another coalition $A_n \in \mathcal{A}'$ to form another partition $\mathcal{A}$ where $n \neq n'$, if and only if $\mathcal{A} \triangleright_u \mathcal{A}'$. That is, the switch operation can be characterized by $\{A_{n'}, A_n\} \rightarrow \{A_{n'} \setminus \{u\}, A_n \cup \{u\}\}$ when $|A_n| < N_n^{\mathrm{RF}}$, or by $\{A_{n'}, A_n\} \rightarrow \{A_{n'} \setminus \{u\} \cup \{u'\}, A_n \setminus \{u'\} \cup \{u\}\}$ when $|A_n| \ge N_n^{\mathrm{RF}}$, where UE u' is selected randomly from A_n.

Given a partition $\mathcal{A}$, its corresponding value of the game depends on the bandwidth fractions allocated for the wireless backhaul and access. The optimal backhaul bandwidth bandwidth for the *n*-th small cell is

$$B_n^{bh*} = \frac{R_n^{ra}}{R_n^{bh} + R_n^{ra}} B. \tag{11}$$

By invoking the wireless backhaul constraint C5 in (6), the optimal backhaul bandwidth of the network must satisfy

$$B^{bh*} = \max\{B_n^{bh*}, \forall n\}. \tag{12}$$

With enough repeating switch operations, the partition will converges to a stable coalition partition according to the coalition structure and switch operation above, in which all players have no incentives deviate from its current coalition. After obtaining the stable coalition partition, the binary association variable $x_{u,n} = 1$ if UE $u \in A_n$, otherwise $x_{u,n} = 0$, and the optimal backhaul bandwidth of the network can be obtained by formula (12). The details of the proposed scheme are summarized in Algorithm 1. Stability is important and

Algorithm 1 Coalition formation algorithm for user association and bandwidth allocation in UDMNs

Initialize the network by a random partition $\mathcal{A}_{ini}$ satisfying all constrains;
Denote the current partition as $\mathcal{A}_c \leftarrow \mathcal{A}_{ini}$;
repeat
  Randomly select a UE $u \in \mathcal{U}$, and mark its coalition as $A_{n'} \in \mathcal{A}_c$, and randomly choose another coalition $A_n \in \mathcal{A}_c$, $A_n \neq A_{n'}$;
  if $|A_n| \geq N_n^{\mathrm{RF}}$ **then**
    Randomly select a UE $u^{'}$ in coalition A_n, assume it swaps with UE u to form a temp partition $\mathcal{A}_{tmp}$, calculate the backhaul bandwidth based on (11) and (12), and obtain the value of the game v according to (9);
    if $\mathcal{A}_{tmp} \rhd_u \mathcal{A}_c$ **then**
      UE u leaves its current coalition A_n and joins the coalition $A_{n'}$;
      UE $u^{'}$ leaves its current coalition $A_{n'}$ and joins the coalition A_n;
      Update the current coalition partition set as
      $\mathcal{A}_c \leftarrow (\mathcal{A}_c \backslash \{A_n, A_{n'}\}) \cup \{A_n \backslash \{u^{'}\} \cup \{u\}, A_{n'} \backslash \{u\} \cup \{u^{'}\}\}$;
    end if
  else
    Assume that the selected UE leaves its current coalition $A_{n'}$ and joins the coalitons A_n to form a temp partition $\mathcal{A}_{tmp}$, calculate the backhaul bandwidth based on (11) and (12), and obtain the value of the game v according to (9);
    if $\mathcal{A}_{tmp} \rhd_u \mathcal{A}_c$ **then**
      UE u leaves its current coalition $A_{n'}$and joins the coalition A_n;
      Update the current coalition partition set as
      $\mathcal{A}_c \leftarrow (\mathcal{A}_c \backslash \{A_n, A_{n'}\}) \cup \{A_n \cup \{u\}, A_{n'} \backslash \{u\}\}$;
    end if
  end if
until The partition converges to the $\mathbb{D}_p$-stable partition.

indispensable for the design of decentralized algorithms. Now, following the similar proof given in [18], [19] and [20], the stability of the proposed coalition formation scheme will be analyzed in the following theorem. For convenience of analyses, we introduce the defection function $\mathbb{D}$ [17], [19], which associates with every network partition. By defining $\mathbb{D}_p$ as a defection function which allows formation of all partition, each player can decide which coalition to join given the partition $\mathcal{A}$.

Definition 3: A partition $\mathcal{A} = \{A_1, A_2, ..., A_N\}$ is $\mathbb{D}_p$-stable if for all partitions $\mathcal{A}^{'} \neq \mathcal{A}$, $v(\mathcal{A}) \geq v(\mathcal{A}^{'})$.

Theorem 1: Starting from any initial partition $\mathcal{A}_{ini}$, Algorithm 1 will always converge to a final partition $\mathcal{A}_{fin}$, which is $\mathbb{D}_p$-stable.

Proof: In Algorithm 1, each switch operation will either result in a new partition or keep current partition. Since there are only N small cells, the maximum number of coalitions is N, which makes the number of partitions be finite. Then, the switch operations will always terminate. Therefore, the network will converge to the final partition $\mathcal{A}_{fin}$ after finite switch operations. Suppose the final partition $\mathcal{A}_{fin}$ is not $\mathbb{D}_p$-stable, there must exit a UE $u \in \mathcal{U}$ that prefers leaving its current coalition and joining another coalition to form another partition $\mathcal{A}_{tmp}$, satisfying $\mathcal{A}_{tmp} \rhd_u \mathcal{A}_{fin}$. This contradicts the fact that $\mathcal{A}_{fin}$ is the final partition. Therefore, the final partition obtained from Algorithm 1 is $\mathbb{D}_p$-stable.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Carrier frequency in LF/bandwidth	2110MHz/10MHz
Carrier frequency in HF/bandwidth	28GHz/200MHz
Radius of macro cell	500m
Radius of small cell	10m
Minimum distance between two SBSs	10m
Thermal noise density	-174dBm/Hz
Shadowing standard deviation	12dB
Path loss	157.4+32$\log_{10}$(R), R in km
side lobe gain z	0.1
Number of RF chains for each SBS	6
Transmit power spectral density of the MBS	-27dBm/Hz
Transmit power spectral density of the SBSs	-47dBm/Hz

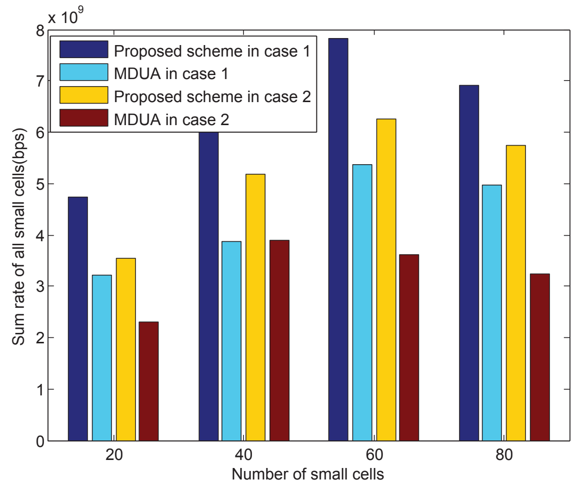

Fig. 3. Sum rate under the proposed scheme and minimum-distance based user association with different numbers of small cells.

IV. Simulation Results

In this section, we conduct simulations to evaluate the performance of the proposed scheme. The small cells are uniformly distributed within the macro cell, and there are four UEs randomly located in the coverage area of each small cell. Other simulation parameters [12], [21] are listed in Table I. The simulations are conducted from the following two case:

- Case 1: The backhaul operation beamwidth and access operation beamwidth are set to $2°$ and $5°$ respectively, which leads to most of small cells' backhaul spectral efficiencies are smaller than their access spectral efficiencies.
- Case 2: The backhaul operation beamwidth and access operation beamwidth are set to $2°$ and $30°$ respectively, which leads to most of small cells' backhaul spectral efficiencies are larger than their access spectral efficiencies.

Fig. 3 shows the system sum rates of our proposed scheme and minimum-distance based user association (MDUA) versus the number of small cells. We can observe that the sum rate increases with the increasing of small cells first, and then decreases with the increasing of small cells in both two cases, which is caused by the increase of the interference as the increasing of small cells. We can also find that the

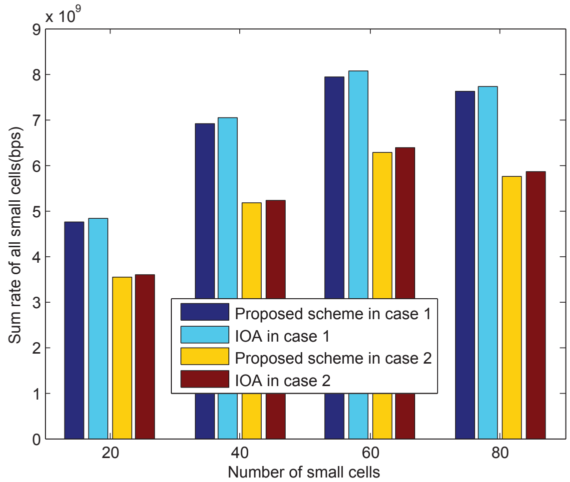

Fig. 4. Sum rate under the proposed game and IOA with different numbers of small cells.

sum rate of the proposed scheme is improved by 39.2% to 78.2% in case 1 and by 32.5% to 78% in case 2 compared to the MDUA. This figure also indicates that the sum rate decreases with the increasing of access operation beamwidth. This is because as the access operation beamwidth increases, the spectral efficiencies of the access links decrease while the spectral efficiencies of backhaul links keep unchanged, which leads to the system bandwidth decreases.

Fig. 4 provides the performance comparison of our proposed coalition game(CG) and the immune optimization algorithm (IOA) used in [11]. Due to the huge amount of complexity of exhaustive search in UDNs, it is prohibitive to use it to obtain the optimal solution in time. Thus we use IOA, which is a popular artificial intelligence algorithm for searching the solution in discrete space, to obtain the solution of the considered problem for comparing with the CG. Here, the main parameters of IOA are as follows: the maximum iteration times are 2000, the size of antibody population is 100, and the crossover probability and the mutation probability are 0.5 and 0.4, respectively. We can observe that the solution of our proposed algorithm approximates that obtained by IOA in both two cases, and the average deviation between the CG and IOA is about 1.6%. Moreover, from the simulation process, we find that the computation time of IOA is about three times of our proposed scheme.

V. Conclusion

In this paper, we proposed a coalition game based joint user association and bandwidth allocation algorithm to maximize the sum rate of all small cells for self-backhaul ultra-dense mmWave networks. The results verify the effectiveness of the proposed algorithm, and provide insights into the effect of mmWave self-backhaul on user association.

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