Client-AP Association for Multiuser MIMO Networks

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***Abstract*—In a Wireless Local Area Network (WLAN), clients typically associate with the AP that offers the maximal signal strength. Later works on client-AP association then further take load balancing and fairness into consideration. Those schemes however are not directly applicable in a multiuser MIMO (MU-MIMO) WLAN since different combinations of clients result in different throughput of each individual client. Therefore, in this paper, we present a client-AP association algorithm customized for MU-MIMO WLANs. The proposed algorithm jointly solves the problems of client-AP association and MU-MIMO client grouping with consideration of channel correlation among clients. It hence allows a good group of clients, i.e., those with low channel correlation, to together associate with the same proper AP and achieve a high sum-rate. The simulation results show that our MU-MIMO AP association algorithm improves the aggregate throughput by about 11%-28% and 26%-45%, as compared to two common association approaches, i.e., RSSI-based and load-based schemes, respectively.**

I. Introduction

The massive number of mobile devices and the emergence of numerous applications, such as video streaming and social networks, together result in large demand for wireless network bandwidth. In order to satisfy this urgent demand, IEEE specifies 802.11n/ac in recent years to exploit MIMO technologies to provide a higher transmission rate for wireless networks. In a MIMO system, each device, i.e., access point (AP) or clients, can be equipped with multiple antennas, which can be used to deliver the spatial multiplexing gain or the diversity gain, or both [1]. MIMO technologies can hence substantially boost the network throughput by not only enabling simultaneous transmissions but also reducing the effect of signal fading.

Recently, 802.11ac is further proposed to enable multi-user MIMO (MU-MIMO) transmissions. In a MU-MIMO system, the AP equipped with multiple antennas can simultaneously transmit (beamform) packets to different clients (with either single antenna or multiple antennas). Concurrent transmissions can be realized by using a signal precessing technique, called zero-forcing beamfoming (ZFBF) [2]. By explicitly precoding the multiple packets, ZFBF eliminates the interference among simultaneous transmissions so that each client only receives its targeted signal. However, such precoding might affect the receiving SNR at each client, and thereby the achievable rate. As shown in previous work [3] [4], the sum-rate of a MU-MIMO network closely depends on channel correlation among concurrent beamformed clients. Therefore, the achievable throughput of a client in a MU-MIMO network not only depends on its receiving signal strength but also the channels of clients that associate with the same AP and could be formed as the same beamforming group.

The above property naturally introduces a new challenge: *How should a client associate with a proper AP with consideration of channel correlation among clients?* In a conventional wireless network, clients usually connect to the AP with the strongest signal strength. Some previous works then proposed to associate clients with the APs such that the load can be distributed evenly among the APs [5] or the overall network throughput can be maximized [6] [7]. However, those approaches do not consider the MU-MIMO scenario where clients can be served simultaneously. Since channel correlation among a group of clients might be different if those clients associate with different APs, AP association in a MU-MIMO WLAN should not only consider the signal strength and traffic load, but also the channels, i.e., channel state information (CSI), from different APs. Therefore, this work aims at investigating the client-AP association problem in multi-cell MU-MIMO networks.

We formulate the joint client-AP association and client grouping problems as a sum-rate maximization model. Due to the NP-hardness of the joint problem, we propose a greedy algorithm to associate each client with a proper AP that allows it to have higher opportunities to find concurrent clients with uncorrelated channels, as a result producing a higher aggregate throughput. Our simulation results show that the proposed algorithm improves the overall throughput by 11%-28% and 26%-45%, as compared to RSSI-based and load-based schemes, respectively.

The rest of our paper is organized as follows. In Section II, we discuss the related works on MU-MIMO client grouping and client-AP association. In Section III, we provide an overview of the ZFBF technique and formulate our system

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model. In Section IV, we present our greedy algorithm. Section V demonstrates the evaluation results of our algorithm. Finally, Section VI concludes this paper.

II. Related Works

The potential of MU-MIMO has been studied both theoretically and empirically. Theoretical works have studied various pre-coding techniques [1] to deliver concurrent streams and analyzed the capacity bound of beamforming [8] [9]. Empirical works also show a practical gain of enabling MU-MIMO in indoor environments [2] [3] [10]. Later literatures then focus on how to select an optimal group of clients to communicate with an AP to enhance the sum-rate of a MU-MIMO network. To avoid the complexity of optimal client grouping, several greedy algorithms are then proposed to find a suboptimal solution. They either iteratively select a client that maximizes the incremental rate [11], [12] or minimizes the interference [13], and hence SNR loss. Our work builds on the basis of the above client grouping approaches, and further investigates how to associate concurrent clients with APs to maximize the sum-rate of a multi-cell MU-MIMO WLAN.

Access point association has been an important research topic for conventional single-user wireless networks. Prior works on AP association mainly focused on optimizing different network parameters, such as fairness [6], throughput [6] [7], interference [7], energy saving [14], handoff frequency [15], power adaptation [16], and load balancing [6]. Some other works [17] [15] then investigated how to realize client association in a distributed way. The above approaches however cannot generally be applied in a multi-user network, where the achievable throughput of a client not only depends on the signal strength and traffic load of its associated AP, but also channel correlation between clients associated with the same AP. Our goal is hence to adjust client-AP association with consideration of client channel correlation in order to achieve maximum possible throughput for MU-MIMO multi-cell wireless networks.

III. System Model

In this section, we first give the background of MU-MIMO networks and then describe our system model.

A. Zero-forcing Beamforming (ZFBF) for MU-MIMO

We consider a downlink MU-MIMO network that consists of an AP equipped with N antennas and a set of clients $\mathcal{U}$. Say the AP serves a group of clients $\mathcal{G} \subseteq \mathcal{U}$ simultaneously, and transmits a symbol s_u to client u, for all $u \in \mathcal{G}$. To eliminate interference, the AP pre-codes (multiplies) each transmitted symbol s_u by a beamforming weight unit vector $\mathbf{w}_u \in \mathbb{C}^{N\times 1}$. The signal received by a client $u \in \mathcal{G}$ can then be expressed by

$$y_u = \sqrt{P_u}\mathbf{h}_u\mathbf{w}_u s_u + \sum_{u'\in\mathcal{G},u'\neq u} \sqrt{P_{u'}}\mathbf{h}_u\mathbf{w}_{u'} s_{u'} + n_u, \quad (1)$$

where P_u is the transmit power allocated to client u, $\mathbf{h}_u \in \mathbb{C}^{1\times N}$ is the channels between the AP and client u, which is independently and identically distributed (i.i.d.) complex Gaussian random variables with zero mean and unit variance, and n_u is the Additive Gaussian White Noise (AWGN) at client u with variance σ_u^2. Note that the sum transmit power should be restricted by the maximum power, i.e., $\sum_u P_u \leq P_{max}$. In Eq. (1), the first term is the target signal for client u, and the second term is the interference from the streams of other clients.

Prior work [18] has shown that finding an optimal beamforming weight vector $\mathbf{w}_u$ for all $u \in \mathcal{G}$ that maximizes the system capacity is a difficult non-convex optimization. Practical systems [2] hence instead exploit a simpler technique, called zero-forcing beamforming (ZFBF), to find the beamforming vectors $\mathbf{w}_u$. In particular, to cancel (null) out the interfering signals at client u, the AP can pick the beamforming vectors $\mathbf{w}_{u'}$ such that $\mathbf{h}_u\mathbf{w}_{u'} = 0$, for all $u' \in \mathcal{G}$ and $u' \neq u$. Such ZFBF ensures that each client u does not see the second interference term in Eq. (1), and hence can exploit the standard decoder to recover the desired signal in the first term.

Let $\mathbf{H}(\mathcal{G}) = [\mathbf{h}_1\mathbf{h}_2\cdots\mathbf{h}_{|\mathcal{G}|}]^T$ be the matrix form of the channel vectors of all clients in the group $\mathcal{G}$, and, similarly, let $\mathbf{W}(\mathcal{G}) = [\mathbf{w}_1\mathbf{w}_2\cdots\mathbf{w}_{|\mathcal{G}|}]$ be the matrix form of the beamforming vectors of all clients in $\mathcal{G}$. According to [19], the ZFBF beamforming matrix can be obtained by the pseudo inverse of $\mathbf{H}(\mathcal{G})$ as follows.

$$\mathbf{W}(\mathcal{G}) = \mathbf{H}(\mathcal{G})^\dagger = \mathbf{H}(\mathcal{G})^*(\mathbf{H}(\mathcal{G})\mathbf{H}(\mathcal{G})^*)^{-1} \quad (2)$$

The sum-rate can be computed through the equation represented as

$$R(\mathcal{G}) = \max_{P_u:\sum_{u\in\mathcal{G}}\gamma_u^{-1}P_u\leq P} \sum_{u\in\mathcal{G}} \log(1+P_u), \quad (3)$$

where

$$\gamma_u = \frac{1}{\|\mathbf{w}_u\|^2} = \frac{1}{\left[(H(\mathcal{G})H(\mathcal{G})^*)^{-1}\right]_{u,u}} \quad (4)$$

can be regarded as the effective channel gain of client u [20]. The optimal power allocation P_u can be determined by the well-known water-filling algorithm. Since different groups of clients result in different system capacities, the AP should explicitly select a proper group of clients for concurrent transmissions. Note that an N-antenna AP can serve at most N clients at the same time. In addition, serving more concurrent clients does not mean improving the sum-rate because channel correlation between clients might increase when more clients are served simultaneously. Therefore, the problem of optimal client grouping for sum-rate maximization can be formulated as

$$\mathcal{G}^* = \arg\max_{\mathcal{G}\subseteq\mathcal{U},|\mathcal{G}|\leq N} R(\mathcal{G}), \quad (5)$$

which can be solved by exhausted search or approximated by greedy algorithms [11]–[13]. For example, the basic idea of exhausted search is to search the best beamforming group $\mathcal{G}^*$ that produces the maximal sum-rate from $\mathcal{U}$, then exclude those clients (i.e., $\mathcal{U} = \mathcal{U}\backslash\mathcal{G}^*$), and repetitively select the best group from the remaining clients in $\mathcal{U}$ until every client belongs to one beamforming group. The average achievable sum-rate of beamforming groups associated with the same AP can then be estimated by

$$R(\mathcal{U}) \approx \sum_{\mathcal{G}\in\mathcal{S}} R(\mathcal{G})/|\mathcal{S}|, \tag{6}$$

where $\mathcal{S}$ is the collection of all the selected groups $\mathcal{G}^*$.

B. Client-AP Association Problem in MU-MIMO

We consider a multi-cell scenario with a set of APs $\mathcal{A}$ and a set of clients $\mathcal{U}$. Each AP $a \in \mathcal{A}$ is equipped with N_a antennas, and can serve at most N_a clients simultaneously. Assume that neighboring APs can leverage spacial reuse, and operate over non-overlapping channels to avoid inter-cell interference. We leave jointly considering the client-AP association and channel assignment problems as our future work. Let $\mathcal{C}_a$ denote the subset of clients that are covered by AP $a \in \mathcal{A}$. Then, each client $u \in \mathcal{U}$ can associate with any of its neighboring APs a if $u \in \mathcal{C}_a$. The clients that finally associate with AP a are collected as a set $\mathcal{U}_a$, and hence $\mathcal{U}_a \subseteq \mathcal{C}_a$.

The achievable sum-rate of an association set $\mathcal{U}_a$ depends on how clients are classified into beamforming groups, as mentioned in Eqs. (5) and (6). To simplify explanation, we use exhausted search to group clients in this work. However, our association algorithm can be combined with any client grouping algorithms. Without loss of generality, we assume that each AP knows the channel state information (CSI) of the clients within its coverage range to perform client grouping. In practice, the CSI of a client can either be estimated by its neighboring APs using reciprocity, or be estimated by clients and reported to the APs. Therefore, our objective is to associate each client with an AP, i.e., determining the proper association set $\mathcal{U}_a$ for all $a \in \mathcal{A}$, with consideration of beamforming grouping in a MU-MIMO downlink transmission scenario such that the sum-rate of all clients $\sum_{a\in\mathcal{A}} R(\mathcal{U}_a)$ can be maximized. Table I summarizes the notations used in this paper, and the above MU-MIMO client-AP association problem can be formulated as follows.

$$\max \sum_{u\in\mathcal{U}}\sum_{a\in\mathcal{A}} r_{u,a} \tag{7}$$

subject to

$$\sum_{a\in\mathcal{A}} I_{u,a} \le 1, \forall u \in \mathcal{U} \tag{8}$$

$$J_{\mathcal{G}_a} \le I_{u,a}, \forall u \in \mathcal{G}_a \in G_a, a \in \mathcal{A} \tag{9}$$

$$\sum_{u\in\mathcal{G}_a\in G_a} J_{\mathcal{G}_a} \le 1, \forall a \in \mathcal{A} \tag{10}$$

$$r_{u,a} = \frac{\sum_{u\in\mathcal{G}_a\in G_a} r_{u,\mathcal{G}_a} J_{\mathcal{G}_a}}{\sum_{\mathcal{G}_a\in G_a} J_{\mathcal{G}_a}}, \forall u \in \mathcal{U}, a \in \mathcal{A} \tag{11}$$

$$I_{u,a} \in \{0,1\}, \forall u \in \mathcal{U}, a \in \mathcal{A} \tag{12}$$

$$J_{\mathcal{G}_a} \in \{0,1\}, \forall \mathcal{G}_a \in G_a, a \in \mathcal{A} \tag{13}$$

We introduce a binary variable $I_{u,a}$ indicating whether client u associates with AP a for all $u \in \mathcal{U}$ and $a \in \mathcal{A}$.

Parameters	Definition
$\mathcal{A}$	the set of APs
N_a	the number of antennas equipped at AP $a \in \mathcal{A}$
$\mathcal{U}$	the set of clients
$\mathcal{C}_a$	the subset of clients that are covered by AP $a \in \mathcal{A}$
$\mathcal{G}_a$	a beamforming group of clients covered by AP $a \in \mathcal{A}$, in which all the member can communicate concurrently with AP a and achieve a non-zero rate
G_a	the set of all candidate beamforming groups covered by AP a
$r_{u,\mathcal{G}}$	the achievable rate of client u if it communicates with AP a when joining group $\mathcal{G}$
Variables	**Definition**
$I_{u,a}$	binary variable indicating whether client u associates with AP a
$J_{\mathcal{G}_a}$	binary variable indicating whether the beamforming group $\mathcal{G}_a \in G_a$ is selected by AP a
$r_{u,a}$	the expected achievable throughput of client u when it associates with AP a
$\mathcal{U}_a$	the set of clients that associate with AP a

TABLE I: Definition of notations

Specifically, $I_{u,a}$ equals 1 if client u is served by AP a, and equals 0, otherwise. Hence, Eq. (8) ensures that each client u associates with at most one AP. We note that, in a MU-MIMO network, the achievable rate of a client depends on channel orthogonality among concurrent clients. That is, a client might achieve a positive throughput when it communicates alone, but get zero throughput when it joins an improper beamforming group, i.e., clients with high channel correlation. Thus, for fair bandwidth sharing, we deem a subset of clients $\mathcal{G}$ as a *candidate beamforming group* only if all the members $u \in \mathcal{G}$ can obtain a non-zero throughput when they communicate concurrently, i.e., $r_{u,\mathcal{G}} > 0$. For ease of representation, we collect all *candidate beamforming groups* of AP a as a set G_a, which is defined as the set of candidate beamforming groups covered by AP a, i.e.,

$$G_a \triangleq \{\mathcal{G} : \mathcal{G} \subseteq \mathcal{C}_a, |\mathcal{G}| \le N_a, r_{u,\mathcal{G}} > 0, \forall u \in \mathcal{G}\}. \tag{14}$$

To model client grouping, we also introduce another binary variable $J_{\mathcal{G}_a}$ to represent whether a candidate beamforming group $\mathcal{G}_a$ is selected. Eq. (9) restricts that a group $\mathcal{G}_a$ can only be selected, i.e., $J_{\mathcal{G}_a} = 1$, if all its members $u \in \mathcal{G}_a$ are associated with AP a, i.e., $I_{u,a} = 1, \forall u \in \mathcal{G}_a$. In addition, each client u can at most join one group, which is constrained by Eq. (10). Eq. (11) indicates that the expected achievable rate $r_{u,a}$ of client u from AP a can be estimated by the rate it obtains from joining group $\mathcal{G}_a$ divided by the number of groups served by AP a, because the capacity of AP a should be shared by all the beamforming groups. Finally, the objective is to maximize the sum-rate of all clients.

We have shown in [21] that the above client-AP association problem in a multi-cell MU-MIMO network is NP-hard. The proof is omitted here due to limited space. Hence, we propose a greedy algorithm that aims at maximizing the sum-rate, while satisfying all the constraints in Eqs. (8–13).

IV. MU-MIMO AP Association Algorithm

The key idea of the proposed greedy algorithm is to iteratively associate a candidate beamforming group with its best AP that contributes the maximum incremental throughput. The iterative association procedure terminates until each of the clients $u \in \mathcal{U}$ is connected to an AP and included in one beamforming group. Algorithm 1 summarizes our greedy algorithm. Recall that G_a is the set of all candidate beamforming groups within the coverage of AP a. We create a set $\mathcal{S}_a$ to collect all the beamforming groups selected to associate with AP a, which is initially set as an empty set $\mathcal{S}_a = \phi$. To pick the group that produces maximum incremental throughput, we estimate the achievable throughput $T(\mathcal{G}_a)$ of all candidate groups $\mathcal{G}_a \in G_a$, for all APs $a \in \mathcal{A}$,

$$T(\mathcal{G}_a) = R(\mathcal{G}_a)/|\mathcal{S}_a \cup \mathcal{G}_a|, \tag{15}$$

where $\mathcal{S}_a$ is the set of beamforming groups that have already associated with AP a. The rationale of the above equation is that each beamforming group should share the medium, and hence the available bandwidth, with other groups that associate with the same AP. Therefore, the actual achievable throughput of a group is not only related to its instantaneous sum-rate, but also depends on the load of its associated AP. In other words, a group could achieve a relatively low throughput if it connects to a heavy loaded AP that already serves many groups, even if the instant sum-rate of the group, i.e., $R(\mathcal{G})$ is high. Here, we assume that all the associated groups share an equal proportion of channel time to communicate with the AP, and hence we can estimate the achievable throughput of a group by its sum-rate divided the number of associated groups. However, some protocols, e.g., 802.11, support packet fairness, instead of time fairness. We can use more sophisticated method, e.g., [22], to estimate the achievable throughput based on the design of the MAC protocol, without affecting the operation of our algorithm. In addition, the throughput estimation can further be modified to consider inter-cell co-channel interference though we assume different APs use different channels in this work.

With the estimated achievable throughput, we can then pick the group along with its associated AP that achieves the maximum throughput gain as follows.

$$\begin{aligned}(a^*, \mathcal{G}^*) &= \arg \max_{a \in \mathcal{A}, \mathcal{G}_a \in G_a} T(\mathcal{G}_a) \\ &= \arg \max_{a \in \mathcal{A}, \mathcal{G}_a \in G_a} R(\mathcal{G}_a)/|\mathcal{S}_a \cup \mathcal{G}_a|. \end{aligned} \tag{16}$$

Once we find the best beamforming group $\mathcal{G}^*$ along with its proper AP a^*, we can associate all the members $u \in \mathcal{G}^*$ with AP a^*, i.e., $\mathcal{U}_a = \mathcal{U}_a \cup \mathcal{G}^*$. After each selection iteration, we discard all the other candidate beamforming groups that contain the clients $u \in \mathcal{G}^*$, as shown in line 7 of Algorithm 1, and also remove the clients in $\mathcal{G}^*$ from the original client set $\mathcal{U}$. The selection procedure is repeatedly executed until $\mathcal{U}$ becomes empty, meaning that all the clients in $\mathcal{U}$ associate with an AP. Therefore, different from conventional client-AP association approaches, our algorithm not only associates clients with proper APs, but also, at the same time, forms beamforming groups that can produce high throughput.

Since most of APs in an enterprise/campus WLAN are connected via backhaul wired networks, our proposed algorithm can be practically realized by delegating a lead AP to perform coordination. One way is to let the lead AP collect the information about the achievable rates of the candidate groups G_a from all APs and solve Algorithm 1. Alternatively, we can reduce the amount of information exchange by iteratively asking each AP to report the achievable sum-rate of its best beamforming group, i.e., $T(\mathcal{G}^*)$, to the lead AP. The lead AP can pick the best client-AP association tuple once it collects all the reports, and announces the results to all the other APs and waits for the next iteration of best group selection. On the other hand, association needs to be updated when the channels of clients change. However, frequent re-association will also cause expensive overhead and oscillation. We hence ask the APs to execute the association algorithm periodically. Deciding the optimal update duration that best balances the tradeoff between the overhead and performance is a potential future research direction.

Algorithm 1 Greedy algorithm for MU-MIMO AP association

Input: set of APs $\mathcal{A}$; set of clients $\mathcal{U}$; set of clients $\mathcal{C}_a$ covered by AP $a \in \mathcal{A}$; set of candidate beamforming groups G_a covered by AP $a \in \mathcal{A}$

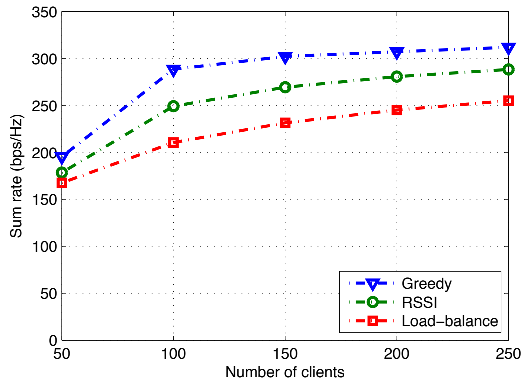
Output: set of clients $\mathcal{U}_a$ associated with AP $a \in \mathcal{A}$

1: $\mathcal{U}_a \leftarrow \{\}$, $\mathcal{S}_a \leftarrow \{\}$ for all $a \in \mathcal{A}$
2: **while** $\mathcal{U} \neq \{\}$ **do**
3: $\quad T(\mathcal{G}_a) = R(\mathcal{G}_a)/|\mathcal{S}_a \cup \mathcal{G}_a|, \forall \mathcal{G}_a \in G_a, a \in \mathcal{A}$
4: $\quad (a^*, \mathcal{G}^*) = \arg\max_{a \in \mathcal{A}, \mathcal{G}_a \in G_a} T(\mathcal{G}_a)$
5: $\quad \mathcal{U}_{a^*} \leftarrow \mathcal{U}_{a^*} \cup \mathcal{G}^*, \mathcal{S}_{a^*} \leftarrow \mathcal{S}_{a^*} \cup \{\mathcal{G}^*\}$
6: $\quad \mathcal{U} \leftarrow \mathcal{U} \backslash \mathcal{G}^*$
7: $\quad G_a \leftarrow G_a \backslash \{\mathcal{G} : \mathcal{G} \in G_a, \mathcal{G} \cap \mathcal{G}^* \neq \phi\}$ for all $a \in \mathcal{A}$
8: **end while**
9: **return** $\mathcal{U}_a$ for all $a \in \mathcal{A}$

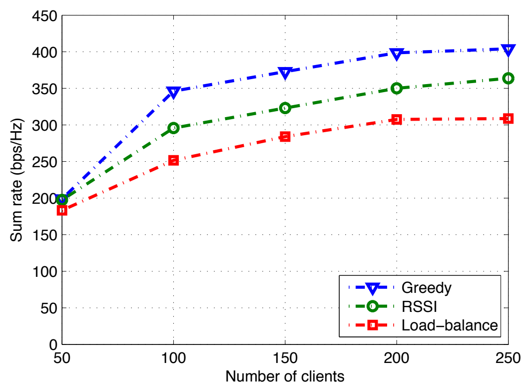
V. Simulation Results

We conduct simulations to evaluate our algorithm in a multi-cell MU-MIMO network. Clients and APs are uniformly randomly distributed in a $500 \times 500m$ square area. Each AP is equipped with 3-4 antennas, while each client is equipped with a single antenna. The communication range of each AP is $150m$. Each node applies the free-space path loss model with the exponent 3. The transmit power is set to 15 dBm, while the noise level is set to -95 dBm. Each adjacent AP uses different channels to enable spatial reuse. We assume that all the clients have continues downlink traffic. Each AP hence transmits concurrent packets to the members of each beamforming group in a round-robin manner.

We compare our greedy algorithm with two association schemes. One is the RSSI-based association scheme, which allows each client to select the AP with the strongest signal strength. The second scheme is the load-balancing association scheme, where the client selects the AP with consideration of the load, i.e., number of served clients, of the APs. To be specific, each client predicts its achievable throughput from all the APs within its coverage range, and selects the one that provides the highest single-link throughput, without considering channel correlation among clients. However, since the throughput estimation depends on the number of clients that have associated with an AP, we let clients sequentially select their suitable APs in a random order. All the comparison

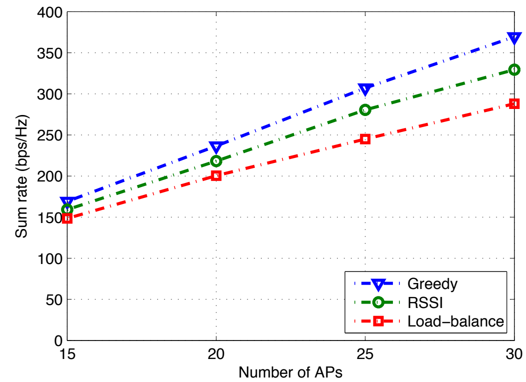


(a) Sum-rate in the 3-antenna AP scenarios

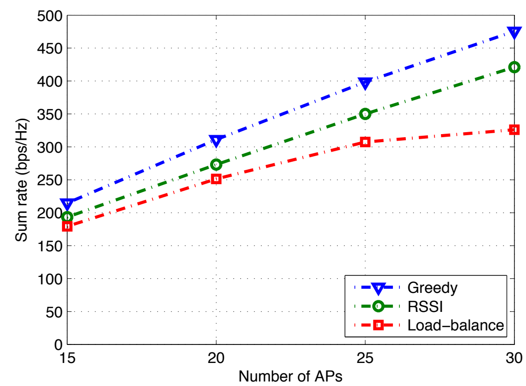


(b) Sum-rate in the 4-antenna AP scenarios

Fig. 1: The performance of varying numbers of clients (25 APs)



(a) Sum-rate in the 3-antenna AP scenarios



(b) Sum-rate in the 4-antenna AP scenarios

Fig. 2: The performance of varying numbers of APs (200 clients)

schemes use exhausted search to find beamforming groups. We check the performance of the comparison schemes for varying numbers of APs, numbers of clients and numbers of antennas equipped at each AP. For each simulation setting, we report the average result of 50 simulation runs.

We first consider the impact of traffic load on the throughput performance by changing the number of clients from 50 to 250. The number of APs is fixed to 25. Figs. 1(a) and 1(b) plot the average throughput of each beamforming group for 3-antenna and 4-antenna APs scenarios, respectively. The results show that the performance of the load-based scheme is even worse than the simple RSSI-based scheme. This illustrates that estimating the throughput without considering channel correlation among clients might overestimate the available bandwidth from an AP, and hence performs worse in a MU-MIMO environment. By jointly considering client grouping, our greedy algorithm outperforms the other two association schemes. The average gain of our greedy algorithm over the RSSI-based and loading-based schemes is 11% (12%) and 26% (28%), respectively, in the 3-antenna (4-antenna) AP scenarios. The maximum gain is up to 15% (17%) and 37% (38%), respectively, when the number of clients is 100. When the number of clients is 50, each AP may cover only a small number of clients, as a result reducing the benefit of diversity. On the other hand, when the number of clients increases, even without proper client-AP association, the AP might still be able to select acceptably good beamforming groups. This explains why the throughput gain for the 250-client case is less significant than the 100-client case. In the 4-antenna AP scenarios, the clients achieve a higher throughput than that obtained in the 3-antenna AP scenarios because the APs can support more concurrent clients. However, the general performance trend of two scenarios are similar.

We then check the performance when the number of APs varies from 15 to 30 and the number of clients is fixed to 200. Figs. 2(a) and 2(b) plot the average aggregate throughput in the 3-antenna and 4-antenna AP scenarios, respectively. The results also show that our proposed greedy algorithm outperforms the two association schemes. In general, the performance of all the schemes increases when there are more APs sharing the traffic load of clients and providing their clients a higher bandwidth. However, without considering channel correlation among clients, the load-based scheme cannot fully utilize the bandwidth of each AP and, hence, its throughput improvement is less significant. In other words, the gain of our greedy algorithm increases as the number of APs increases because each client has more association choices. The maximum gain over the load balancing scheme is 28% (45%) for 3-antenna (4-antenna) AP scenarios when the number of APs is 30.

In Fig. 3, we examine the performance when the number of APs' antennas changes from 2 to 7. In this simulation, we fix

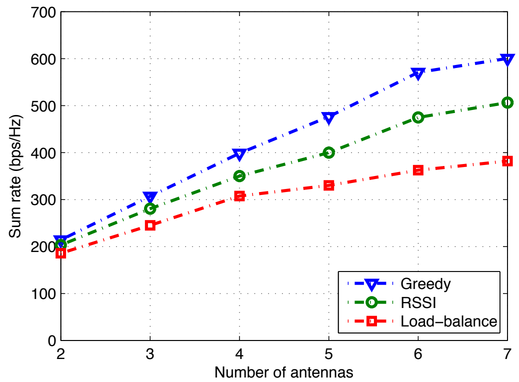


Fig. 3: Varying number of antennas at each AP (25 APs, 200 clients)

the number of APs and clients to 25 and 200, respectively. The figure shows that our algorithm outperforms the other schemes and the gain over the RSSI-based and load-based scheme increases as the number of AP's antennas increases. This is because, when the number of concurrent clients increases, the probability that any two concurrent clients have correlated channels also increases, as a result decreasing the average rate of a beamforming group. In this case, careful client grouping and AP association become more important. This explains why our algorithm can benefit more from increasing the number of antennas at each AP.

VI. Conclusions

In this paper, we consider the problem of client-AP association in an MU-MIMO WLAN. We have formulated the joint problems of client-AP association and client grouping as a mathematical model. Due to the NP-hardness of the joint problem, we propose a greedy algorithm that computes the achievable sum-rate of each beamforming group based on channel orthogonality among clients and then iteratively associates the best beamforming group with its optimal AP that produces the maximal sum-rate. Our evaluation shows that the proposed algorithm achieves a throughput gain of 11–28% and 26–45% over the RSSI-based and load-based schemes, respectively.

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