Distributed Fair Access Point Selection for Multi-Rate IEEE 802.11 WLANs

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Abstract—For the mobile users (MUs) installed with IEEE 802.11 wireless adapters, the default best-signal-strength-based access point (AP) selection is limited since it does not consider fairness and multi-rate issues. In this paper, we propose a distributed AP selection algorithm for newly joining MU and already associated MUs to be adaptive to their joining order and the dynamic wireless environment. We also prove the stability of proposed algorithm and analyze its complexity. Finally, with extensive evaluations, we show that proposed scheme can greatly improve the fairness without significantly sacrificing the efficiency.

I. INTRODUCTION

With the fast development of wireless local area networks (WLANs), it’s very important for the mobile users (MUs) to select a right access point (AP) [1]. Even though operational WLANs have shown that users tend to geographically cluster in the network, the default best-RSSI(receiving signal strength indicator)-based AP selection scheme does not provide any fair sharing functionality. Many studies like [5] show that the naive RSSI-based method leads to bad MU-AP associations that result in severe unfairness and poor overall performance. On the other hand, in [4], the authors show the notorious unfairness feature (performance anomaly) of IEEE 802.11 for the MUs with different data rates in a single AP cell. In the topology with multiple APs, it’s mandatory for us to utilize the multi-rate information to design a better AP selection scheme.

There have been numbers of researches done on this particular issue. Generally speaking, they can be divided into two categories: centralized optimal and distributed heuristic methods. The centralized optimization-based schemes can provide accurate optimal solutions by executing additional software on a control center in the network [2], [7]. However, it’s not practical to let one control center collect all the information inside the network and distribute the association commands to the MUs. On the other hand, the distributed schemes are more friendly to current trend of ubiquitous networking and adaptive to the dynamic wireless environment [3]. However, due to its lacking of consideration of the multi-rate feature, the performance can be even worse than the default RSSI-based scheme under some circumstances. In [9], the authors propose an AP selection mechanism to allow HRFA (high-rate first association) in IEEE802.11e WLANs. However, the ordinary WLANs with multi-rate adaptation are much more widely deployed and required to be carefully investigated.

In this paper, we propose a distributed fair AP selection scheme based on a heuristic algorithm that can be implemented by adding one additional field in current AP beacon and probing packets, and some low complexity operations on the MUs. The fairness we addressed is specially referred to as the max-min MU throughput fairness that is already widely studied in the networking literature [8]. For given AP selection problem, we show the corresponding relationship between improving MU throughput fairness and improving AP load balancing. Furthermore, we prove the stability of the proposed distributed algorithm and analyze the complexity.

The rest of this paper is organized as follows. Section II describes the assumptions and definitions used in this paper. Section III introduces the detailed selection algorithm and the analysis of it. Section IV shows the performance of proposed algorithm by numerical and discrete event evaluations. Finally, the conclusions are summarized in Section V.

II. SYSTEM MODEL AND RELATED WORK

A. Assumptions and Definitions

To simplify the study, we assume that the neighboring APs are configured with different non-overlapping channels as most of other existing AP selection studies. The set of APs and MUs are denoted as $\mathcal{A}$ and $\mathcal{U}$, respectively. We let the set of associated MUs be $\mathcal{U}_a \subseteq \mathcal{U}$ for AP $a$ and the set of APs that can provide service for MU $u$ as $\mathcal{A}_u \subseteq \mathcal{A}$. We use $r$ to denote the MU physical data rate, where $r_{ua} > 0$ means that MU $u$ can be served by AP $a$ with a valid data rate in the predefined bit rate set of IEEE 802.11 standards, and $r_{ua} = 0$ means MU $u$ is out of the transmission range of AP $a$. In this work, we also assume that the traffic on each MU is saturating uplink UDP link.

Although the objective we study should naturally be in the domain of MU throughput, the corresponding load on the AP is highly correlated. We refer to the definition of AP load from...
and give the approximated expression of MU throughput from [6].

**Definition 1**: (AP load and MU throughput): The load on an AP $a \in A$, denoted by $y_a$, is the aggregate period of time that takes AP $a$ to provide a unit of traffic volume to all its associated users $u \in U_a$. Thus

$$y_a = \sum_{u \in U_a} \frac{1}{r_{ua}}. \quad (1)$$

The approximated throughputs of MUs associated with this AP are identical due to performance anomaly [4] and can be denoted as

$$\theta_u = \frac{1}{y_a}. \quad (2)$$

Note that, we can neglect the MAC (Media Access Control) header and other overhead in the MAC layer because if we assume the same packet length in the top logy, the proportion $p$ of actual throughput achieved above the MAC layer tends to be a constant value for different data rate, for example, $p \approx 0.70$ for IEEE 802.11b with 1500 bytes [4]. Therefore, the result of AP selection scheme will not be affected by this approximated throughput model.

The fairness objective we choose in this study is max-min MU throughput fairness. Due to space limitation, we skip the detailed introduction of max-min fairness, min-max balancing, and leximin/leximax ordering that are already well defined in [8]. Note that, leximin ordering, a concept borrowed from economics, can be used to compare the extend of fairness between two MU throughput vectors. Given two vector $\vec{x}$ and $\vec{y}$ with the same size, the method to compare the leximin ordering is first to sort the elements of them in non-decreasing order and then compare the corresponding values by index. We say $\vec{x}$ has better leximin ordering than $\vec{y}$ ($\vec{x} \geq\text{lex} \vec{y}$) if and only if $(\exists i)x_i > y_i$ and $(\forall j < i)x_j = y_j$. Therefore, the max-min MU throughput fairness defines the leximin maximal vector.

### B. Problem Formulation and Discussion

Formally, in a WLAN topology with AP set $A$ and MU set $U$, we define the fair AP selection problem of this paper as using a fully distributed scheme to achieve max-min fairness among the MUs in terms of throughputs.

The main theorem in [2], which says that the MU-AP association resulting in max-min MU throughput fairness also leads to the min-max AP load balancing, is valid if one MU can be associated with multiple APs. However, it does not hold in our ordinary WLAN (one MU can only select one AP) due to the mapping from AP load vector and MU throughput vector is not unique. Thus, we can extend this main theorem for proposed distributed AP selection algorithm design with the following lemma.

**Lemma 1**: For normal AP selection, increasing the leximin ordering of MU throughputs results in decreasing the leximax ordering for AP loads and vice versa.

**Proof**: The duality relationship holds because the increment of any MU’s throughput must result in the decrement of its associated AP’s load according to Eqs. (1) and (2). Since this lemma is straightforward and based on the definition of leximin/leximax ordering, we skip the detailed proof here.

### C. Related Work

In [2], Bejerano and others formulate the problem of AP selection for max-min MU throughput fairness’s based on integer linear programming (LP). Due to its NP-hardness, the authors relax the integer formulation (integral selection, i.e., each MU can only be associated with a single AP) to a continuous problem (fractional selection, i.e., each MU might be associated with multiple APs). They then use LPs plus rounding to get a 2-approximation algorithm. Another work reported in [7] formulates the AP selection for proportional fair sharing. However, it only provides theoretical study and numerical results without any specific algorithm proposed. The schemes mentioned above [2], [7] are all centralized. It means an additional control center should be deployed for collecting information and distributing association commands. Intuitively, it not only leads to additional equipment and management cost but also violates the ubiquitous feature of current WLAN development.

On the other hand, in [3], Fukuda and others propose a distributed metric-based AP selection method to address fair sharing by evaluating $\frac{1-P_a}{N_a}$, where $P_a$ is the PER (packet error rate) and $N_a$ is the number of MUs served by that AP $a$. However, the important property of multi-rate in current IEEE 802.11 standard is out of scope in their work. Moreover, the authors in [9] propose a distributed fair algorithm incorporating the data rate information by calculating medium time to give more priority to high-rate associations. However, the proposed algorithm is dependent on the specific features of IEEE 802.11e that is not widely deployed.

### III. Distributed AP Selection Algorithm

In this section, we will present our distributed AP selection scheme for both APs and MUs. Especially, we present the algorithm, shown in Algorithm 1, running on MUs with two cases: the newly joining MUs that is going to select an AP and the existing MUs that is already associated with an AP in the network. Then, we prove the stability of our algorithm and analyze the complexity of it.

#### A. Modification on the APs

On each AP, in order to notify the current AP load to the MUs, one additional field will be added to the packets of beacon and probe response. Moreover, since the wireless environment is dynamic in nature and some MUs can move in and out occasionally, the APs should keep recording the physical data rates of its active associated MUs. We should also note that frequently changing the association of the MUs

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1Although we can easily extend our scheme with PER, we don’t consider it here since we assume the background noise is uniform anywhere in the scenario.
Algorithm 1 Distributed AP selection algorithm for MU \( \hat{u} \).

1: MU \( \hat{u} \) joins the WLAN.
2: Send probe request packets to all channels.
3: Receive the probe response packets with AP load information \( y_a \) and the mostly possible data rate \( r_{ua} \).
4: For all reachable APs, calculate the estimated AP load vector by calculating Eq. (4).
5: The MU \( \hat{u} \) select the AP as \( \arg \min_{a \in A_{\hat{u}}} \hat{y}_a \).

LOOP with interval \( \Delta \)
6: Sending probe request packets to the channels of available neighboring APs
7: Receive the probe request packets and update the estimated AP load by calculating Eq. (4).
8: if Switching to \( a' \) lead to \( y_a - y_{a'} > \delta \) then
9: MU \( \hat{u} \) switches the association to \( a' \).
10: end if
ENDLOOP

Algorithm 1.

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leximax ordering of AP loads is decreased and the leximin ordering of MU throughputs is increased according to Lemma 1. According to the Proposition 1 in [8], which says the max-min fair MU throughput vector solution is unique, we can conclude that the AO will stop after finite number of operations.

Note however that, even with AO, the effect of joining order can not be totally eliminated. Therefore, we can not guarantee to reach the max-min MU throughput by proposed scheme with AO. However, according to the simulation results, we can observe that the performance of our scheme is very close to the centralized scheme proposed in [2].

The operation of APs is very simple with the proposed modification. Considering this, let’s review the complexity of our algorithm on the MUs. For the newly joining MU, it only needs to send probe request packets to all channels. If AO is enabled, the additional overhead for one MU is the periodical probing operation every $\Delta$ seconds on $|A_u|$ channels.

IV. PERFORMANCE EVALUATION

In this section, we first use numerical evaluation for larger-scale topology evaluation to clearly show the theoretical performance between centralized and distributed schemes. We then provide NS2 simulation results for smaller scale topologies. We modify the IEEE 802.11 MAC source code in NS2 with the capability of periodically sending beacons and exchanging probing messages on different channels. The beacon interval is configured as 100ms according to IEEE 802.11 standard. The interval of updating the AP load filed $\Omega$ on APs and the interval of probing procedure $\Delta$ for AO on MUs is configured as one and 15 seconds, respectively. We use total throughput $\sum_{u \in U} \theta_u$ as the metric to evaluate the efficiency. Also Jain’s fairness index

$$\frac{(\sum_{u \in U} \theta_u)^2}{|U| \times \sum_{u \in U} \theta_u^2},$$

is used to measure the degree of fairness. We compare proposed AP selection algorithm with RSSI-based scheme and Fukuda’s scheme [3]. To show the effect of AO, we implement our distributed algorithm with and without AO and then compare them with the performance of Bejerano’s centralized fair scheme [2].

A. Numerical Evaluation

We generate a random topology of size $2000 \times 2000m^2$ with 15 APs and 100 MUs. After applying different selection algorithms, we calculate the MU throughputs. To illustrate the distribution of MU throughputs, we sort all throughputs and plot them with log scale in Y-axis with respect to the MU index as shown in Fig. 2. On the other hand, since the results of proposed scheme and Bejerano’s scheme are very close, we plot the number of MUs with respect to the throughput range in Fig. 3. The overall performance about throughput and fairness is summarized in Table I.

According to Fig. 2, apparently, the RSSI-based selection scheme does not provide any load balancing feature so that the maximal MU throughput is much larger than the minimal throughput (around 20 times) and the fairness index value 0.29. The reason is that when many MUs cluster in several AP cells, some MUs in less-congested AP cells achieve very high throughputs. On the other hand, although Fukuda’s scheme can guarantee fair sharing among the MUs, it actually leads to the worst total throughput that is only about 1/4 of RSSI-based scheme. This result clearly shows that the necessity of considering the impact of low data rate MUs, which is missing in their scheme. On the other hand, the performance of Bejerano’s centralized scheme and proposed algorithm shows similar performance. However, the centralized scheme achieves around 20Mbps more total throughput and 1Mbps more minimal throughput at the cost of deploying a centralized control center. According to Fig. 3 and Table I, we can clearly observe that Bejerano’s centralized scheme and proposed scheme with AO has no MUs with throughput less than 5Mbps. Also proposed algorithm without AO has more than 10 MUs with throughput less than 5Mbps. Moreover, proposed scheme with AO will lead to the majority of MU throughput distributed in the range of 6Mbps that is less than 7Mbps of centralized scheme. Therefore, if we compare the leximin ordering for the results of these three schemes, we can have Bejerano’s scheme $\geq_{lex}$ proposed scheme with AO $\geq_{lex}$ proposed scheme without AO.
placed in the $600 \times 600m^2$ topology. Around 20 MUs are distributed in the topology and AP1 is deliberately overloaded by half of the MUs. The traffic on each MU is constant 2Mbps UDP traffic to the associated AP. Accordingly, we can see that proposed scheme with AO not only shows better total throughput but also almost double fairness index value than RSSI-based scheme. Fukuda’s scheme still shows the lowest total throughput but with fair MU throughputs.

V. Conclusions

In this paper, we propose a fully distributed and self-stabilizing AP selection scheme for WLANs. By extensive simulations, we can observe that our scheme can improve the throughput fairness among the MUs without greatly sacrificing efficiency among the MUs comparing with other distributed schemes.

REFERENCES