Throughput Measurement-based Access Point Selection for Multi-rate Wireless LANs

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Abstract. In this paper, we propose a novel access point (AP) selection algorithm to maximize the system throughput while considering user fairness. The main idea is that when a new-coming user enters an overlapping area of a wireless local area network (WLAN), it first estimates the system throughput as if it were associated with each of the APs involved. Then it chooses the AP that can achieve the highest system throughput. For existing users that locate in the overlapping area, they may also need to change the AP association due to the dynamic nature of traffic load. To enable the fairness among users, each user is guaranteed the minimum transmission opportunity. Another significant contribution of this paper is that we find that load-balancing based approaches could not achieve the maximum throughput for multi-rate WLANs, although load-balancing has been considered as an effective approach to improve the network throughput for single-rate WLANs. In-depth theoretical analysis and extensive simulations are performed to verify the throughput optimization and user fairness.

1 Introduction

With the extensive applications of WLANs and the increasing number of wireless users, network administrators often deploy multiple APs in a WLAN to improve the network capacity. To better take the advantage of this deployment, one problem must be carefully attacked. That is, which AP should be associated with if a user has multiple APs reachable. The traditional AP selection method is signal strength first (SSF) [1], which is known to degrade the system throughput because a significant number of users may be associated with a few APs. Another problem of the signal-strength based methods is the fairness. Users associated with heavy-load APs have less transmission opportunity than other users associated with light-load APs.

To address the throughput issue, many algorithms are developed based on the idea of load balancing. The assumption here is that the system throughput can be maximized as long as the load among the APs are well balanced. While numerical results have suggested considerable improvement on throughput, these algorithms only work for single-rate WLANs. In multi-rate WLANs, a user may generate load varied dramatically to different APs. If the load-balancing approach were used in multi-rate WLANs, it is likely that users are prone to choose APs in which they generate heavier load and thus lead to poor throughput.

Throughput and fairness are both significant metrics to evaluate the network performance. The reality, however, is that they are often contradictory goals. In this paper, we develop a novel AP selection algorithm for multi-rate WLANs. The objective of the algorithm is to maximize the system throughput while taking fairness into account. Our two significant contributions can be summarized as follows.

• A novel AP selection algorithm, named Throughput Measurement-based Selection (TMS) is presented and analyzed. In TMS, a user in the overlapping area selects the AP so that it makes the most increment to the overall system throughput regardless of the throughput or the load of the AP being chosen. Notice that both new-coming users and existing users are carefully handled in our algorithm. To address the fairness issue, we introduce a new concept, called *opportunity fairness*, into the time allocation scheme for users within the same AP.

• A new finding on throughput maximization is presented. Load-balancing has been commonly considered as an effective approach to improve the system throughput for single-rate WLANs. In this paper, however, we prove that the load-balancing approach could not necessarily achieve the maximum throughput for multi-rate WLANs. This is because a user may generate dramatically different load to different APs depending on its transmission rate in multi-rate WLANs.

The rest of paper is organized as follows. In Section II, we briefly introduce some related work. Section III presents the network model and problem statement. In Section IV, we present the detailed design of the Measurement-based Selection (TMS) algorithm. The performance evaluation is presented in Section V. Concluding remarks are given in Section VI.

2 Related Work

The traditional AP selection method–SSF first drew researcher's attention because it was believed that the uneven load distribution caused the throughput degradation. Consequently, the starting point of most approaches is to distribute the load to all APs as equal as possible. Unfortunately, there is no common definition of the load. In [2, 3], the number of current users of an AP is assumed as the load of an AP. All users are assumed to have the same transmission rate regardless of the distance between a user and an AP in above approaches. However, this is obviously not true for multi-rate WLANs. In our paper, we use a more realistic definition of load by factoring the diversity of transmission rates.

Recently, several other strategies based on load balancing are proposed for multi-rate WLANs. The least load first (LLF) [4] is one of popular heuristic methods. In LLF, a new-coming user selects the AP with the least load, without factoring its own load. Another load balancing technique by controlling the size of WLAN cells is proposed in [5]. This method is similar to cell breathing in cellular networks, which allows APs to adjust their coverage areas by varying the transmission power of beacon frames.

It is acknowledged that fairness measure is another indispensable concern in allocating system sources to multiple users or applications. In [4], an association control is employed to achieve max-min fair bandwidth allocation. They consider load balancing as an efficient to obtain max-min fair bandwidth allocation. A distributed max-min fairness AP selection method extended from LLF (we call it ELLF in this paper) is proposed in [6]. In ELLF, new-coming users select the AP with the least load factoring its own load, to maximize the new users' throughput. Nevertheless, this local throughput optimization of one user is not identical to the overall system throughput maximization. [7] considers proportional fairness in a network of APs. They proposed two approximation algorithms for periodical offline optimization to achieve proportional fairness.

Generally, most of above papers are based on the idea of load balancing to achieve either maximum system throughput or optimal user fairness. While system throughput and user fairness are both significant metrics to evaluate the network performance, in most cases, there is a tradeoff between them. The trade-off relationship of system throughput and fairness with quality of service support is addressed in [8]. An interference-limited wireless network is considered and call admission control is used.

Maximizing network throughput while considering user fairness is one of the critical challenges in WLANs. In our paper, the ultimate objective is to optimize the overall system throughput while maintaining user fairness. To maximize the throughput, we propose a novel Throughput Measurement-based AP Selection algorithm, instead of load balancing. Due to the trade-off between system throughput and user fairness, it is meaningful only when comparing the efficiency of different algorithms based on the same fairness definition. To maintain user fairness, we introduce an opportunity fairness scheme and all methods are performed based on this fairness strategy.

3 Network Model and Problem Statement

3.1 Network Model

Let U denote the set of all users in the entire system and $N_U = |U|$ the number of users. Let A denote the set of all APs and $N_A = |A|$ the number of APs. Each AP is assigned a dedicated non-overlapping channel. We assume each AP has a limited transmission range, and it only serves the users within its range. Only users in the overlapping coverage of multiple available APs are able to be re-associated. Concerning the association model, all the users can only communicate with one AP at any time as in the single-association model. Meanwhile, for the incoming traffic flow, we assume all users are greedy so that they always have traffic to transmit. We define an $N_A \times N_U$ matrix X to denote the associations between users and APs, whose element $x_{a,u}$ is a binary variable, that is: $x_{a,u} = 1$ if the user u associates with AP a and otherwise $x_{a,u} = 0$. And U_a is a set including all users associated with AP a. Transmission rate is a significant parameter in our AP selection algorithm. We introduce an $N_A \times N_U$ matrix R to represent the transmission rate between users and APs, whose element $r_{a,u}$ is the transmission rate of user u to AP a. Another important parameters in our algorithm is load. Here we adopt the definition of load from [4], that is, for user

u, the load $l_{a,u}$ generated on its associated AP a is inversely proportional to its transmission rate $r_{a,u}$. The load of an AP then can be defined as follows:
Definition 1 (*Load of an AP*): The load of AP a, denoted by l_a, is the sum of load induced by all of its associated users, that is,

$$l_a = \sum_{u \in U_a} l_{a,u} = \sum_{u \in U_a} \frac{1}{r_{a,u}}. \tag{1}$$

3.2 Opportunity Fairness

Users associated with the same AP share the same communication channel to AP. Thus an access scheme is needed to allocate the channel access. In order to improve the effective utility of channel and guarantee the fairness among users within the same AP, we introduce a concept named *opportunity fairness* and provide a novel time allocation scheme to multi-rate users. In our scheme, we do not assign equal time to all its users in the same AP. Instead, varied time is allocated to users based on their transmission rates and packet sizes. We define transmission opportunity $O_{a,u}$ for user u connected to AP a as the number of packets transmitted in a time period T. The ideal user fairness means that all users should be allocated an equal opportunity. However, there is a trade-off between system throughput and user fairness. In order to improve the network throughput, faster users should be granted more opportunities. On the other hand, it is important that no users be starved. Thus each user must be allowed to transmit at least one packet in each time period. Here we design a ε-Opportunity Fairness definition as follows:
Definition 2 (*ε-Opportunity Fairness*): User fairness among all the users associated with AP a is defined as the ratio of the maximum transmission opportunity to the minimum transmission opportunity of users, that is, $\varepsilon_a = \frac{\min(O_{a,u})}{\max(O_{a,u})}, \varepsilon_a \in (0, 1]$.

3.3 Problem Statement

Definition 3 (*Throughput*): The throughput of AP a, denoted by θ_a, is the number of packets successfully transmitted in a unit time, that is,

$$\theta_a = \frac{\sum\limits_{u \in U_a} (O_{a,u} \cdot x_{a,u})}{\sum\limits_{u \in U_a} (\frac{O_{a,u} \cdot x_{a,u}}{r_{a,u}})} = \frac{O_a}{L_a}, \tag{2}$$

where O_a represents the total number of packets transmitted in a period time and L_a denotes the time used to transmit all O_a packets. We address that the throughput of an AP is not only determined by its load, but also the transmission opportunity of its associated users. Our objective is to maximize the throughput while maintaining opportunity fairness among users. Therefore, the optimized throughput problem with fairness constraint can be defined as:

$$\max \sum_{a \in A} \theta_a$$

subject to

$$\sum_{a \in A} x_{a,u} = 1, x_{a,u} \in \{0,1\} \tag{3}$$

$$\frac{\min(O_{a,u})}{\max(O_{a,u})} \geq \varepsilon, \varepsilon \in (0,1] \tag{4}$$

$$O_{a,u} \geq 1. \tag{5}$$

Constraint (3) represents that each user is associated with only one AP at a time. Constraint (4) represents that the opportunities can not vary dramatically between fast and slow users. Constraint (5) guarantees that no user be starved.

4 Algorithm and Analysis

In this section we present the throughput measurement-based AP selection algorithm to optimize the system throughput. The focus here is the throughput of the entire system rather than of a single AP. We measure the contribution of each user to the overall system throughput. A user selects the AP in which its contribution is maximized. Notice that the chosen AP may not be the one has the highest throughput among all APs. To reduce the computational complexity, the decision is eventually made based on the increment of the system throughput instead of the absolute throughput value. Given the dynamic nature of WLANs, AP associations for both new-coming users and existing users are considered. Therefore, each AP needs to periodically update the information, such as traffic load and the transmission opportunities of associated users.

4.1 For New-Coming Users

We consider the new-coming users that enter the overlapping area of multiple APs. With an attempt to maximize the system throughput, the new-coming user first estimates the system throughput as if it accessed each available AP. It then selects the AP such that the system throughput will be the highest one. Denote the current throughput of each AP by θ_a $(a = 1, 2, ..., N_A)$ and the corresponding system throughput as $\theta = \sum_{a=1}^{N_A} \theta_a$. A new-coming user u enters the system and has several available APs. Suppose that user u chooses AP m, the new system throughput then is:

$$\begin{aligned} \theta^* &= \frac{O_m + O_{m,u}}{L_m + O_{m,u} \cdot l_{m,u}} + \sum_{a=1, a \neq m}^{N_A} \theta_a \\ &= \begin{cases} \theta + \frac{O_{m,u} \cdot L_m - O_{m,u} \cdot O_m \cdot l_{m,u}}{(L_m + O_{m,u} \cdot l_{m,u}) \cdot L_m} & l_m \neq 0 \\ \theta + \frac{1}{l_{m,u}} & l_m = 0 \end{cases} . \end{aligned}$$

Denote $D_{m,u}$ as:

$$D_{m,u} = \begin{cases} \frac{O_{m,u} \cdot L_m - O_{m,u} \cdot O_m \cdot l_{m,u}}{(L_m + O_{m,u} \cdot l_{m,u}) \cdot L_m} & l_m \neq 0 \\ \frac{1}{l_{m,u}} & l_m = 0 \end{cases} . \tag{6}$$

The new throughput θ^* can be represented as: $\theta^* = \theta + D_{m,u}$.

Comparing θ with θ^*, new-coming user u makes a contribution $D_{m,u}$ to the overall system throughput. Notice that $D_{m,u}$ may be a negative value. We call $D_{m,u}$ the contribution to the system throughput when it attempts to associate with AP m. The contribution of the same user to different APs may vary significantly, depending on the factors such as rates, the throughput of current AP, and the transmission opportunity of the chosen AP's users. Therefore, user u should choose the AP with the maximum $D_{m,u}$, which leads to the maximum throughput of the entire system not of the single AP.

It can be seen from (6) that $D_{m,u}$ is a combination of several measurements, such as the load of a new-coming user and the transmission opportunity of the current users. Therefore, this method is more comprehensive to improve the system throughput. On the other hand, it is not necessary to calculate the system throughput estimation when a new-coming user comes, but $D_{m,u}$. All the parameters of $D_{m,u}$ is only from the new-coming user and the AP it attempts to associate with. In this way, the computational complexity can be greatly reduced compared to overall system throughput calculation.

4.2 For Existing Users

Realizing the fact that new-coming users have influence on the existing users and the fact that WLANs environment varies with time, the associations of existing users should be changed dynamically to maximize the system throughput. Suppose that an existing user v in AP j switches to AP k. Before switching, the system throughput is: $\theta = \sum\limits_{a \neq j,k} \theta_a + \theta_j + \theta_k$, where the throughput of AP j and k can be represented as:

$$\theta_j + \theta_k = \begin{cases} \frac{O_j}{L_j} + \frac{O_k}{L_k} & l_k \neq 0 \\ \frac{O_j}{L_j} & l_k = 0 \end{cases} . \tag{7}$$

After switching, the system throughput is changed to: $\theta^* = \sum\limits_{a \neq j,k} \theta_a + \theta_j^* + \theta_k^*$, where the new throughput of AP j and k is:

$$\theta_j^* + \theta_k^* = \frac{O_j - O_{j,v}}{L_j - O_{j,v} \cdot l_{j,v}} + \frac{O_k + O_{k,v}}{L_k + O_{k,v} \cdot l_{k,v}} . \tag{8}$$

$\theta_j^* + \theta_k^*$ in (8) may be larger, smaller or equal to $\theta_j + \theta_k$ in (7). We define their difference as $D_{j,k,v}$:

$$D_{j,k,v} = \theta_j^* + \theta_k^* - (\theta_j + \theta_k), \tag{9}$$

which is also the difference of the system throughput due to the fact that user v switches from AP j to AP k. When $D_{j,k,v} > 0$, the re-association will benefit the system throughput. Hence, we let user v change its association from AP j to AP k. To avoid frequent re-associations, we impose a constraint on the difference, that is, $D_{j,k,v} > \delta, (\delta > 0)$. The proposed AP selection algorithm is summarized in **Algorithm 1**.

Algorithm 1 Measurement-based AP Selection Algorithm

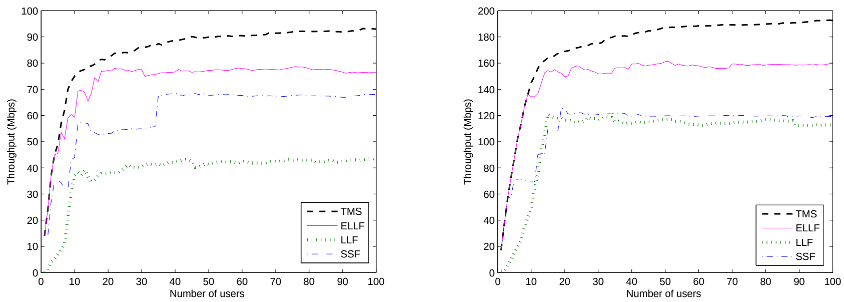
```
Periodically update the information for each AP
Update matrix X
Update O_{a,u} of each user
Update the current throughput θ_a by (2)

For new-coming users
if u is a new-coming user in the coverage of only one AP then
  Choose this AP for user u
else
  Estimate D_{m,u} by (6) for each available AP m
  Choose the AP with max(D_{m,u})
end if

For existing users
for existing user v(v ∈ U_j) in the overlapping area of more than one AP do
  for each available AP k do
    Find the largest one max(D_{j,k,v}) by (9)
    if max(D_{j,k,v}) > δ then
      User v switch to the AP with max(D_{j,k,v})
    end if
  end for
end for
```

5 Performance Evaluation

In this section, we evaluate the performance of our proposed TMS algorithm in comparison with three other popular methods: Strongest-Signal-First (SSF), Least-Load-First (LLF), and Extension of LLF (ELLF). We assume the transmission rate is determined by the distance between APs and users. Our algorithm is performed iteratively and new users join WLANs one bye one. Two experiments are conducted with different opportunity fairness criteria. In each experiment, all APs are uniformly deployed and all users are deployed randomly. The transmission rate between a user and its APs follow Discrete Poisson distribution with a parameter $\lambda = 10Mbps$.

5.1 1-Opportunity Fairness

In the first experiment, we conduct the performance evaluation based on 1-Opportunity Fairness, that is, $\varepsilon_a = \frac{\min(O_{a,u})}{\max(O_{a,u})} = 1$. The 1-Opportunity Fairness indicates that all the users within a same AP have the equal transmission opportunities, which is the ideal opportunity fairness among users. We compute the system throughput with the users coming based on R. Fig. 1(a) and 1(b) illustrate the system throughput under 10 APs and 15 APs, respectively. Both figures demonstrate that TMS achieves notable system throughput improvement compared with other methods. In Fig. 1(a), the system throughput of TMS is improved about 20% compared to ELLF, 33.3% to SSF, even 125% to LLF. In Fig. 1(b), the advantage of TMS on system throughput is more significant: about 26.7% improved to ELLF, 58.3% to SSF and LLF.



(a) With 10 APs and 100 users (b) With 15 APs and 100 users

Fig. 1. Comparison of the system throughput with different methods: TMS, ELLF, LLF and SSF under 1-Opportunity Fairness

Comparing Fig. 1(a) and Fig. 1(b), with the increasing number of APs, the number of users in the overlapping area of APs are correspondingly increased. At the same time, the increasing number of APs brings more capacity. Both factors contribute to the significant improvement of system throughput. Specifically, the maximum throughput is improved from about 90 Mbps with 10 APs to 180 Mbps with 15 APs. The average of maximum throughput per AP increases about 33.3%.

The load balancing is measured using Jain Index [9] as :$J = (\sum_{a=1}^{N_A} l_a)^2/(N_A \cdot \sum_{a=1}^{N_A} l_a^2)$. Table 1 lists the load balancing degree for 10 and 15 APS with 100 users, respectively. The load balancing of LLF and ELLF outperforms in both cases. This result validates the idea that LLF and ELLF are designed based on load balancing. TMS is relatively low in terms of load balancing. The lower load balancing in TMS is rather reasonable because the idea of TMS is based on the increment of system throughput, rater than load balancing. The results further prove that load balancing is not the appropriate strategy to achieve optimal system throughput in multi-rate WLANs, on the premise of maintaining the same fairness among users.

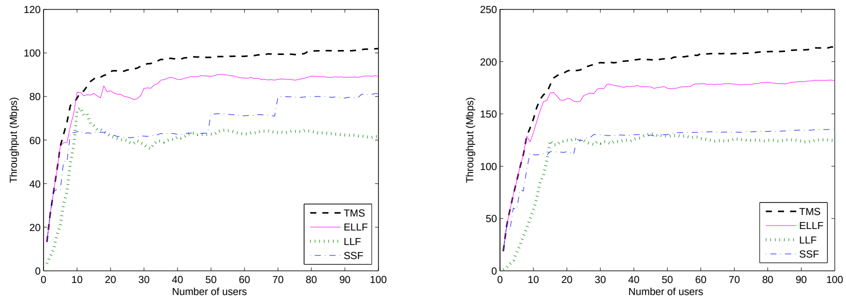
Table 1. 1-Opportunity Fairness: Load balancing degree Among APs

Load Balancing	TMS	ELLF	LLF	SSF
Average Jain Index (10 APs and 100 users)	0.5383	0.9015	0.8972	0.4165
Average Jain Index (15 APs and 100 users)	0.5881	0.8471	0.8223	0.2871

5.2 ε-Opportunity Fairness

In the second experiment, we conduct the performance evaluation based on ε-Opportunity Fairness ($\varepsilon \in (0, 1)$). We provide a transmission opportunity design as: $O_{a,u} = \lceil \frac{r_{a,u}}{min(r_{a,u})} \rceil, u \in U_a$. The corresponding user fairness within one AP then can be calculated as: $\varepsilon_a = \frac{\min(O_{a,u})}{\max(O_{a,u})}, u \in U_a$. In this experiment, we use the same deployment of APs and users and transmission rate matrix R as in the first experiment. The only difference is that the user fairness is changed to ε-Opportunity Fairness.

Fig. 2(a) is the counterpart of Fig. 1(a) and Fig. 2(b)is the counterpart of Fig. 1(b) Both Figs. 2(a) and 2(b) once again verify that our proposed algorithm TMS has higher system throughput in ε-Opportunity Fairness situation compared with other methods. In Fig. 2(a), the system throughput of TMS is improved about 17.6% compared to ELLF and 66.7% to LLF. In Fig. 2(b), the system throughput of TMS is improved about 14.3% to ELLF, 60% to SSF and LLF.



(a) With 10 APs and 100 users

(b) With 15 APs and 100 users

Fig. 2. Comparison of the system throughput with different methods: TMS, ELLF, LLF and SSF under ε-Opportunity Fairness

Next, we compare the system throughput on 1-Opportunity Fairness and ε-Opportunity Fairness. Observing Fig. 1(a) with Fig. 2(a), and Fig. 1(b)with Fig. 2(b), the system throughput of ε-Opportunity Fairness ($\varepsilon < 1$) is apparently improved about 10% compared with the corresponding system throughput in 1-Opportunity Fairness situation ($\varepsilon = 1$). The reason of the system throughput improvement is that faster users have more transmission opportunities in ε-Opportunity Fairness compared with the transmission opportunities in 1-Opportunity Fairness.

Table 2 lists the average Jain Index which represents the load balancing degree among APs in ε-Opportunity Fairness. The same conclusion with 1-Opportunity Fairness can be derived: the load balancing of LLF and ELLF are better in both Tables. TMS is relatively low in terms of load balancing among APs. Through numerical experimentations on the relationship between system throughput and load balancing, it shows that a higher throughput may come along with a lower load balancing. However, there is no sufficient evidence to prove that this is of inherent. So we can not conclude that there is an inverse proportional correlation between the system throughput and load balancing degree in multi-rate WLANs.

Table 2. ε-Opportunity Fairness: Load Balancing Degree Among APs

Load Balancing	TMS	ELLF	LLF	SSF
Average Jain Index (10 APs and 100 users)	0.4188	0.9012	0.9071	0.4712
Average Jain Index (15 APs and 100 users)	0.3077	0.8312	0.8501	0.5617

6 Conclusions

In this paper, we have presented a novel AP selection algorithm to obtain high system throughput while maintaining opportunity fairness among users. Extensive simulations with both 1-Opportunity Fairness and ε-Opportunity Fairness demonstrate that our proposed algorithm significantly improves the system throughput, as compared with three other popular schemes while maintaining the same fairness.

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