# Association Scheme with Traffic Control for IEEE 802.11 Wireless LANs

Jaeseon Hwang, Hyuk Lim, Seunghun Oh, and Byung-Tak Lee

## Abstract

In wireless LANs, wireless clients are associated with one of access points (APs) to obtain network connectivity, and the AP performs network traffic relay between the wired infrastructure and wireless clients. If a client with a low transmission rate is associated with an AP, the throughput performance of all the clients that are associated with the AP is significantly degraded because of the long channel usage time of the low-rate client. Therefore, it is important to select an appropriate AP when a new client joins the wireless LAN to prevent the performance degradation. In this paper, we propose a traffic control that determines the feasible data traffic from an AP to the clients on the basis of the trade-off relationship between the equal-throughput and equal-airtime traffic allocation policies. We then propose a network-wide association algorithm that allows a client to be associated with the AP that can provide the highest throughput improvement. Simulation results indicate that the proposed algorithm achieves the better aggregate throughput and throughput fairness performances in IEEE 802.11 WLANs.

## Index Terms

Traffic allocation, AP selection, association, wireless networks.

## I. INTRODUCTION

Recently, network management for wireless local area networks (WLANs) has received substantial attention because of the rapid increase in the number of users and throughput demands of mobile devices such as laptops, smart phones, and tablet devices. In order to provide Wi-Fi

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connectivity to mobile devices, a number of access points (APs) have been widely deployed in public areas such as hotels, campuses, and cafes. Owing to this widespread deployment, multiple APs are often available to a client that wishes to be connected to wireless networking. From the set of available APs, the client needs to select the AP and has to send a joining request message to it. Through these processes called *association*, the client is associated with one of APs and is ready to use the Internet services.

The IEEE 802.11 WLAN standard [1] defines two service sets for wireless networking: a basic service set (BSS) and an extended service set (ESS). An IEEE 802.11 BSS network consists of an AP and a group of clients associated with the AP, and an IEEE 802.11 ESS consists of a set of two or more BSSs. In an BSS network, wireless clients are associated with a single AP and are connected to Internet through the AP. Each client competes with other clients that are associated with the same AP for a wireless channel in accordance with the IEEE 802.11 Distributed Coordination Function (DCF). In literature, it has been reported that the throughput performance of a BSS network is significantly degraded when some clients use relatively low transmission rates [2]. This is called *performance anomaly*, and researchers have studied traffic control at either an AP or a client side [3]–[13] to overcome the performance anomaly by adjusting the channel usage time of each client. Because each wireless network access the channel with an equal channel access probability in average sense, a suitable traffic allocation method needs to be designed for multi-rate clients to prevent the excessive channel use time of low-rate clients and increase network throughput performance in BSS networks.

In an ESS network, wireless clients that want to join the network identify an appropriate AP by exchanging a probe request/response frame with the available candidate APs. IEEE 802.11 WLAN standard does not define any association scheme for this functionality. One of association schemes used in practice for implementation is to use a received signal strength indicator (RSSI). In an RSSI-based association scheme, a client broadcasts a probe request frame on a current channel and measures the RSSI value of the corresponding probe response frame sent by an AP. After scanning all the channels, the client selects the AP with the strongest RSSI value. Unfortunately, this RSSI-based association scheme does not guarantee the highest throughput for the associated clients because the AP that has the strongest RSSI value may be already overloaded with an excessive number of associated clients. Therefore, it is desirable to distribute traffic loads over other APs with less traffic load in order to provide better quality of service

(QoS) to the associated clients. An association scheme that enables a client to select the AP with the smallest number of associated clients has been proposed. However, this scheme does not guarantee high throughput performance because some clients may select an AP that is located far away from themselves. A number of advanced association schemes for achieving high throughput performance have been proposed [14]–[21] that consider various channel conditions and traffic loads. Because the throughput performance of an ESS network is an aggregate throughput of APs in BSS networks, it is important to deal with the association problem along with the traffic control for wireless clients in BSS networks to provide high performance wireless network connectivity.

In this paper, we first propose a hybrid traffic allocation algorithm for use in an IEEE 802.11 BSS network. This algorithm allows the AP to properly assign traffic loads to its associated clients based on two traffic allocation policies: one considering the throughput and the other considering the channel access time. The proposed traffic allocation control method can increase network throughput performance while ensuring a certain level of fairness. For IEEE 802.11 ESS networks, we propose a network-wide association algorithm, which enables a new client to select the AP to be associated with among the candidate APs in the ESS network for maximizing the network throughput performance. Finally, we present the simulation results, which indicate that the proposed algorithm achieves the better network throughput and throughput fairness performances than other conventional algorithms.

The main features of the proposed algorithm are twofold. First, the proposed traffic allocation algorithm, which is based on a simple linear combination of two well-known policies, can precisely control the trade-off relationship between the aggregate throughput and throughput fairness with a single control parameter in order to mitigate the performance anomaly in WLANs. Second, the proposed association algorithm can predict the throughput performance of clients in an ESS of WLAN because the traffic amount for each client is under the control, and enables wireless clients to be associated with the AP that can give the largest increase of network-wide throughput performance. Conventional association schemes without traffic control cannot guarantee that wireless clients achieve a certain level of throughput and fairness performance when they are associated with an AP.

The rest of this paper is organized as follows. In Section II, we summarize the related research work with respect to association and traffic control methods. In Section III, we review two existing traffic allocation policies and then propose a hybrid traffic allocation algorithm for a

BSS network. We propose a network-wide association algorithm in Section IV, based on the hybrid traffic allocation algorithm, for an ESS wireless network. We present simulation results in Section V, and this paper is concluded in Section VI.

## II. RELATED WORK

### A. Association control

Association control has been extensively studied in order to overcome the inefficiency of the RSSI association scheme. Some researchers proposed to exploit the available bandwidth information for selecting AP in association procedures. In [14], the authors proposed an estimation scheme for the uplink and downlink bandwidth based on beacon delays and empirically evaluated it on a real wireless testbed. Lee *et al.* [15] proposed to use the available bandwidth information for network throughput maximization. An association metric called EVA was formulated on the basis of the IEEE 802.11 DCF. When EVA is used, each client estimates the maximum achievable bandwidth for available AP candidates and tries to select the AP that can provide the maximum throughput. Gupta *et al.* [16] also utilized the available bandwidth for association control in wireless mesh networks. Gong and Yang [22] proposed an AP association algorithm based on its analytical model for heterogeneous clients in IEEE 802.11n WLANs, where each client obtains the achievable bandwidth proportional to its data rate.

A number of studies that consider channel conditions and traffic loads have been conducted. Bejerano *et al.* [17] showed the relationship between load balancing and fair bandwidth allocation, and presented an association control scheme for network-wide max-min fair bandwidth allocation. In [18], two association mechanisms were proposed with a new association framework in order to reflect channel conditions. One of the mechanisms is a channel-quality-based association, in which every client estimates SINR values on the uplink and the downlink for candidate APs and then selects the AP that can provide the minimum packet error rate. In the second scheme called the airtime-association scheme, APs and clients measure downlink and uplink loads, and then the client selects the AP with the smallest traffic load. In [19], the authors proposed a cross-layer association scheme for wireless mesh networks, in which the end-to-end airtime cost is mainly used to determine an association target node, and conducted the experimentation with the off-the-shelf Wi-Fi devices in a multi-hop wireless network testbed. Cui *et al.* [23] proposed centralized and distributed AP association algorithms to achieve AP load-balancing for multimedia services in multi-hop wireless mesh networks. Sundaresan and Papagiannaki [20] proposed that one metric is not sufficient to reflect network conditions. They considered three metrics, i.e., the RSSI, the transmission delay, and the AP capacity, to determine the client throughput for selecting an AP. In our proposed algorithm, a client selects the AP that can provide the highest network throughput performance while ensuring a certain level of fairness among the multiple candidate APs.

In [24], the authors considered joint resource allocation and BS assignment for the downlink in CDMA networks. They attempted to solve the power and rate allocation problem in order to maximize the throughput performance for the downlink in the single cell. Then, the result for a single cell was extended to multi-cellular system with multiple BSs, where there existed heavily loaded and lightly loaded cells. The authors proposed a pricing-based BS allocation algorithm, which eventually balanced the traffic load among the BSs, and resulted in higher throughput performance, especially when there were a number of mobile clients and the loads on BSs were asymmetric. Our proposed algorithm focuses on a tradeoff relationship between the throughput and fairness performance, and provides a control knob for adjusting the airtime of clients in order to maximize the network throughput performance while ensuring a target fairness performance in Wi-Fi networks. Unlike [24], the proposed algorithm does not change the transmit power of clients, but instead, for a given transmission power and rate, it adjusts the airtime usage of clients by regulating the amount of traffic for each client in order to mitigate the performance anomaly in WLANs.

### *B. Traffic control*

Researchers have proposed a number of algorithms that adjust the channel usage time of each client through traffic control in order to resolve the performance anomaly. Yang *et al.* [3] presented an analytical model for a multi-rate wireless LAN and proposed several methods, which consisted of controlling MAC parameters such as the backoff window and frame size, in order to reduce the performance degradation due to low-rate clients. Babu and Jacob [4] also presented analytical models for achieving time-based fairness and investigated the impact of using the models on MAC parameters. In [5], [6], the authors proposed the enhanced backoff mechanisms that adjust the contention window size of each client to achieve better network throughput and fair channel access. Chou *et al.* [7] proposed two schemes based on the contention window size and the AIFS value defined in IEEE 802.11e. Lin *et al.* [8] proposed a threshold based traffic control technique that dynamically adjusts the load threshold at each gateway to achieve a fair traffic load distribution in wireless mesh networks. The TFCSMA algorithm proposed by Joshi *et al.* [9] changes channel access opportunities by adjusting the minimum contention window size to ensure airtime fairness among clients. Huang *et al.* [10] proposed a maximum buffer allocation algorithm that resolves the unfairness problem between uplink and downlink of TCP flows by allocating more buffer space to downlink TCP DATA packets. Zhang and Bensaou [25] presented an optimization framework to achieve a fair downlink bandwidth allocation between clients in dense WLANs. Khawam *et al.* [26] formulated an optimal centralized algorithm with a game theoretic approach, where each client reduces its data transmission time, in order to minimize the network cost. In [11], [12], the authors proposed the fairness based algorithms that maximize the throughput performance under a fairness constraint in multi-rate wireless LANs. Our proposed algorithm differs from these schemes in that it enables an AP to regulate the channel usage time of its associated clients based on two traffic allocation policies in order to increase network throughput performance and to ensure a certain level of fairness.

In [13], Tan and Guttag proposed a time-based regulator (TBR) scheme, which runs on the AP and provides long-term time-based fairness. TBR is based on the leaky bucket scheme [27], and it schedules frame transmissions based on the token rate of each client. By adjusting the token rate, the channel usage time of high-utilization clients is distributed to low-utilization clients in order to maintain high channel utilization for all clients. Similarly, our proposed algorithm employs the leaky bucket scheme at the AP in order to precisely provide the amount of allocated traffic to its associated clients.

## III. Traffic Control for IEEE 802.11 BSS Networks

In an IEEE 802.11 wireless LAN, an ESS consists of one or more interconnected BSSs, where APs are directly connected to a wired network infrastructure and relay network traffic between the wired infrastructure and their associated clients. Let $A$ denote a set of APs, and let $C(a)$ denote a set of clients associated with an AP $a \in A$. In this section, we focus on the traffic allocation problem for a BSS network, where a single AP provides internet connectivity to its associated clients through wireless channels. The AP and the clients are assumed to be backlogged with a number of data packets in their buffer. In accordance with the IEEE 802.11

DCF, all the clients compete for a wireless channel, and the one whose backoff counter reaches zero, grabs the channel and transmits a data frame. Because the selection is randomly performed, depending on the backoff mechanism, the overall network throughput may decrease if a client with a low SNR seizes the channel for a long time, owing to the low transmission rate of that client. To the contrary, if an AP is allowed to actively regulate the channel usage time of each node by using a traffic allocation policy, the overall network throughput can be dramatically increased.

### *A. Traffic allocation policies with traffic feasibility*

We consider traffic allocation for wireless clients associated with an AP in a BSS network. First, we define traffic feasibility, which enables us to decide whether an AP can provide a given amount of traffic to its associated clients within a given time duration. We next review two existing traffic allocation policies that can ensure traffic feasibility: the equal-throughput allocation (*ET*) policy and equal-airtime allocation (*EA*) policy[1].

**Traffic feasibility:** Let us suppose that an AP relays data traffic to its associated clients. If an AP $a \in A$ is able to transmit data frames to each associated client $c \in C(a)$ during a channel access time $T$, all traffic loads $s(a,c)$ (bps) are *feasible* when the following inequality is satisfied [17]:

$$T \cdot \sum_{c \in C(a)} \frac{s(a,c)}{r(a,c)} \leq T, \tag{1}$$

where $r(a,c)$ is a transmission rate between AP $a$ and client $c$. Depending on the SNR, an appropriate transmission rate $r(a,c)$ can be determined from the SINR-rate mapping table [28]. Then, an amount of traffic $s(a,c) \cdot T$ can be transmitted with a rate of $r(a,c)$ during a time duration $T$, and $\frac{s(a,c) \cdot T}{r(a,c)}$ is the data transmission time. For example, if an AP $a$ can transmit $s(a,c) = 100$ kbps traffic load with a rate of $r(a,c) = 1$ Mbps to a client $c$, the data transmission time is given by 0.1 $T$. This implies that ten percentage of the time duration $T$ is used for serving the traffic load. If the transmission rate is higher, a shorter time duration is needed for the transmission.

Another important factor that is related with the traffic feasibility is the backbone network capability of each AP. If the aggregate bandwidth of clients that is associated with an AP is greater

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[1] From the viewpoint of fairness, these policies are often referred to as the throughput fairness and time fairness, respectively.

than the backbone network capacity, the clients may experience the throughput performance degradation such as packet losses and delays.

**Equal-throughput allocation:** This policy enables an AP to allocate an equal amount of traffic to each associated client during its channel access time $T$. In this case, all clients obtain the same throughput performance even when their transmission rates are different. Let $s^{ET}(a,c)$ be the throughput from an AP $a$ to the client $c$, in accordance with the equal-throughput allocation policy. Then, all the clients have an equal throughput value of $s(a,c) = s^{ET}(a,c)$. When the equality of Equation (1) holds, the allocated traffic vector $s^{ET}(a)$ is given by

$$\begin{aligned} s^{ET}(a) &= \left[ s^{ET}(a,1), s^{ET}(a,2), \cdots, s^{ET}(a, |C(a)|) \right]^{\mathrm{T}} \\ &= \frac{1}{\sum_{c \in C(a)} \frac{1}{r(a,c)}} \cdot \mathbb{1}_{|C(a)|}, \end{aligned} \tag{2}$$

where $\mathbb{1}_x$ is the 1's column vector of dimension $x$. Since the throughput is the same for all the clients, it can be said fair in terms of the throughput performance. However, if low-rate clients exist, the aggregate network throughput is degraded because they have an extremely long transmission time due to the low transmission rate.

**Equal-airtime allocation:** This policy enables an AP to allow each associated client to have an equal channel access time. Since the AP distributes the total channel access time $T$ among $|C(a)|$ associated clients, the equal channel access time for each client is $\frac{T}{|C(a)|}$. When the equality of Equation (1) is satisfied, the time period for each client is the same and is given by

$$\frac{s(a,i)}{r(a,i)} = \frac{1}{|C(a)|} \text{ for } \forall i \in C(a).$$

Depending on the transmission rate, the allocated traffic vector $s^{EA}(a)$, under the equal-airtime allocation policy, is represented as follows:

$$s^{EA}(a) = \frac{1}{|C(a)|} \left[ r(a,1), r(a,2), \cdots, r(a, |C(a)|) \right]^{\mathrm{T}}. \tag{3}$$

For each client, the throughput is proportional to the corresponding transmission rate. Hence, the throughput fairness deteriorates when clients use different transmission rates. Even though the throughput fairness is degraded in this type of allocation policy in comparison with the equal-throughput allocation policy, the throughput performance increases because the AP transmits a large amount of data to high-rate clients without scarifying the airtime for low-rate clients.

TABLE I

Comparison between the equal-throughput and the equal-airtime allocation policies.

| Metrics | Traffic allocation | |
|---|---|---|
| | ET | EA |
| Aggregate throughput | Low | High |
| Throughput fairness | High | Low |

**Summary:** Table I compares the equal-throughput allocation policy with the equal-airtime allocation policy in terms of the aggregate throughput and throughput fairness performance. The aggregate throughput can be increased with the equal-airtime allocation policy, whereas the throughput fairness can be achieved with the equal-throughput allocation policy. Therefore, there is a trade-off relationship between the aggregate throughput and throughput fairness for both policies.

### *B. Proposed hybrid traffic allocation algorithm*

To adjust the performance in terms of the aggregate throughput and throughput fairness, we propose a hybrid traffic allocation (HA) algorithm, which is a combination of the equal-throughput and equal-airtime allocation policies. The steps involved in this hybrid traffic allocation algorithm are as follows. First, based on the number of associated clients and their transmission rates, an AP $a \in A$ computes the throughput value of each client for each policy, i.e., $s^{ET}(a)$ and $s^{EA}(a)$, using Equations (2) and (3), respectively.

Next, the AP $a$ computes a column vector $s^{HA}(a;\gamma)$ consisting of the hybrid throughput of each client with a weighting factor as follows:

$$s^{HA}(a;\gamma) = \gamma \cdot s^{ET}(a) + (1-\gamma) \cdot s^{EA}(a), \tag{4}$$

where $\gamma$ is a weighting factor ($0 \le \gamma \le 1$). We now represent $\mathcal{S}_a(\gamma)$ as the aggregate throughput of the AP $a$, which is the summation of hybrid throughput $s^{HA}(a;\gamma)$, as follows:

$$\mathcal{S}_a(C(a);\gamma) = (s^{HA}(a;\gamma))^{\mathrm{T}} \cdot \mathbb{1}_{|C(a)|}. \tag{5}$$

When AP $a$ provides data traffic to clients $C(a)$, we use $\mathcal{S}_a(C(a);\gamma)$ to denote the set of associated clients. Finally, AP $a$ precisely regulates the allocated traffic load $s^{HA}(a,c;\gamma)$ for each client $c$ by employing the leaky bucket algorithm [27], which is a traffic shaping algorithm. As $\mathcal{S}_a(C(a);\gamma)$ depends on the value of $\gamma$, we derive the characteristics of the aggregate throughput and throughput fairness in terms of $\gamma$ when there are $n$ number of clients associated with an AP in a BSS network.

**Theorem 1.** *Consider a BSS network in which a single AP provides network traffic to n number of associated clients. As $\gamma$ increases, the aggregate throughput monotonically decreases, whereas the throughput fairness monotonically increases.*

*Proof.* See Appendix. □

Note that the aggregate throughput and throughput fairness are highly affected by the value of $\gamma$ from the derivation. There is a trade-off relationship between the aggregate throughput and throughput fairness. When $\gamma$ is zero, the throughput of low-rate clients is significantly degraded, but aggregate throughput is increased because the equal-airtime allocation policy is followed. As $\gamma$ increases to 1, the AP follows the equal-throughput allocation policy more closely. As a result, the throughput fairness is improved but the aggregate throughput is degraded. Because an ESS network consists of one or more interconnected BSSs, both the throughput and fairness performance result can be easily extended to the ESS network.

## IV. ASSOCIATION CONTROL FOR IEEE 802.11 ESS NETWORKS

An ESS consists of one or more interconnected BSSs, and its throughput is given by the summation of AP throughputs as follows:

$$\mathcal{S}_n(\gamma) = \sum_{a\in A} \mathcal{S}_a(C(a);\gamma). \tag{6}$$

Using the traffic allocation algorithm in (5), each AP determines the appropriate amount of traffic to be allocated to its associated clients and actively controls the airtime usage in accordance with $\mathcal{S}_a$ for $a \in A$. Because $\mathcal{S}_a$ depends on the number of clients and their transmission rate, it can be used to predict $\mathcal{S}_a$ for an AP $a \in A$ when a new wireless client joins the AP $a$.

We propose a network-wide association algorithm for a new client in order to increase the network throughput performance while ensuring a certain level of fairness. For association, a new client has to first select an AP from among multiple candidate APs. To identify the appropriate AP, the client obtains the current throughput $\mathcal{S}_a(C(a);\gamma)$ and the expected throughput

**Algorithm 1** BS association algorithm with traffic control for a new client

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• For each available AP $a \in A$,
    (S1) a new client $c$ sends a probe request frame to the AP $a$.
    (S2) AP $a$ determines the transmission rate $r(a, c)$, based on the SINR value measured from the probe request frame.
    (S3) AP $a$ carries out the hybrid traffic allocation algorithm using Equation (4), in order to compute its current throughput and expected throughput, assuming that client $c$ is associated with AP $a$.
    (S4) AP $a$ responds with the probe response frame containing the current and expected throughputs, namely, $\mathcal{S}_a(C(a); \gamma)$ and $\mathcal{S}_a(C(a) \cup \{c\}; \gamma)$.
• The client selects the AP that provides the highest throughput gain from among the available APs using Equation (7).
• The selected AP regulates the traffic allocated to its associated clients by running the hybrid traffic allocation algorithm using Equation (4).
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$\mathcal{S}_a(C(a) \cup \{c\}; \gamma)$ for every $a \in A$ when the client $c$ is associated with the AP $a$. Based on the obtained values of throughputs, the client selects the AP that can provide the highest throughput gain among the candidate APs for maximizing network throughput performance as follows:

$$a^* = \arg\max_{a \in A}(\mathcal{S}_a(C(a) \cup \{c\}; \gamma) - \mathcal{S}_a(C(a); \gamma)). \tag{7}$$

After the association, the selected AP performs precise traffic allocation for its associated clients, including the new client, by using the hybrid traffic allocation algorithm in (4).

Algorithm 1 describes the procedure of the proposed association algorithm when a new client joins an ESS network. First, the client sends a probe request frame to each AP $a \in A$. After receiving the probe request frame, the AP determines the transmission rate $r(a, c)$ between itself and the client according to the SINR value of the probe request frame. While the probe request frame is sent at a fixed transmission rate, the AP can measure the SINR value of the probe request frame, and determines the maximum data transmission rate using an SINR-rate mapping table for the Wi-Fi network interface [28]. Note that the SINR value is given by the ratio of the received signal power at the receiver and the interference-plus-noise. The received power can be easily obtained from the RSSI value [29], which primarily depends on the distance and wireless channel between the AP and the client, due to the fact that the power level of a transmitted signal attenuates over distance. The interference-plus-noise is very difficult to directly measure, and thus, it is assumed to be a certain level of thermal noise of the receiver. In (S3) of the algorithm, the AP executes the hybrid traffic allocation algorithm in order to compute two aggregate throughput values, $\mathcal{S}_n(C(a);\gamma)$ and $\mathcal{S}_n(C(a)\cup\{c\};\gamma)$. Next, it responds with the probe response frame containing the two computed throughput values in (S4). With the two throughput values received, the client computes the throughput gain, which indicates the amount of increase in throughput for that particular AP. After determining the capability of traffic provisioning from the throughput gain of all available APs, the client selects the AP that can provide the highest throughput improvement. Finally, the selected AP regulates network traffic for its associated clients by executing hybrid traffic allocation in the BSS network.

Algorithm 1 assumes that the wireless channel is reciprocal for the downlink and uplink, and the interference-plus-noise level is the same at the AP and client. Under this assumption, once the AP determines the transmission rate for uplink traffic where the AP is the receiver according to the SINR value of the probe request frame sent by a client, it is then used for the downlink traffic regulation as well as the AP association. However, it would be possible that the SINR at an AP is different from that at its clients because the Wi-Fi device is different and a level of interference is also different. In this case, it is required that each client measures the SINR for the probe response frame sent by APs and adjusts the transmission rate $r(a,c)$ by taking the minimum of the rates. This modification would be a simple extension of Algorithm 1, and the detailed implementation issue is omitted in this paper.

In Algorithm 1, the selected AP is responsible to regulate the traffic for each client associated with itself. However, the demand for uplink traffic becomes rapidly increasing. For example, a photo upload service for smart phone users uploads a large-sized image file to a cloud storage whenever a photo is taken [30]. Therefore, it is highly required to devise an efficient traffic regulation scheme for uplink traffic in Wi-Fi networks. However, the uplink traffic regulation for distributed clients is quite difficult because of its carrier sensing and backoff mechanism, and it would remain as our future work.

In addition, it is also important to select an appropriate value of $\gamma$ that guarantees a certain level of fairness. In this paper, we employ Jain's fairness index [31] as a fairness performance metric. The fairness for all clients is represented by $F(\gamma)$, which is an increasing function of

$\gamma$ according to Theorem 1. In order to obtain the maximum network throughput performance $\mathcal{S}_n(\gamma)$ while ensuring a target fairness of $F$, the optimal $\gamma$ is selected as follows:

$$\gamma^* = \arg\max_{0 \le \gamma \le 1} \mathcal{S}_n(\gamma)$$
$$\text{subject to} \quad F(\gamma) \ge F. \tag{8}$$

Since $\mathcal{S}_n(\gamma)$ is a decreasing function according to Theorem 1, the throughput performance is the highest when $\gamma$ is the smallest. Therefore, the optimal $\gamma^*$ can be obtained when the achieved fairness is the same as the target fairness.

## V. PERFORMANCE EVALUATION

To evaluate the performance of the proposed algorithm, we have implemented the proposed algorithm in *ns*-2 (version 2.33) [32] and have conducted extensive simulations to compare it with the RSSI and least-association algorithms. The default parameters used in the *ns*-2 simulations are presented in Table II. We consider IEEE 802.11a multi-rate wireless LANs in which all nodes are within transmission range from each other. We assume that adjacent APs use orthogonal channels to avoid the effects of interferences and that each AP relays constant bitrate (CBR) traffic with the packet size of 1000 bytes. The data rate is determined by the distance between the AP and client, and it is one of the eight transmission rates supported by the IEEE 802.11a. The basic rate is fixed at 6 Mb/s. Due to the IEEE 802.11 DCF overhead,[2] the feasible amount of traffic is lower than that computed by Equation (4). In the proposed algorithm, the system parameter $\gamma$ is set at 0.5 for reflecting throughput and fairness in the same degree. As a fairness metric, Jain's fairness index [31] is used and it is represented in A. In these simulations, there may exist hidden clients depending on a network topology. If either of a probe request frame by a new client or its corresponding probe response frame collides due to hidden APs or clients, the association algorithm in Algorithm 1 would fail, and thus, the client retries the association.

### A. *Fixed topology*

We considered an example network topology shown in Fig. 1(a), where two APs are located at the corners and ten clients are skewed toward AP 1 in a network with a size of a 50 m × 50

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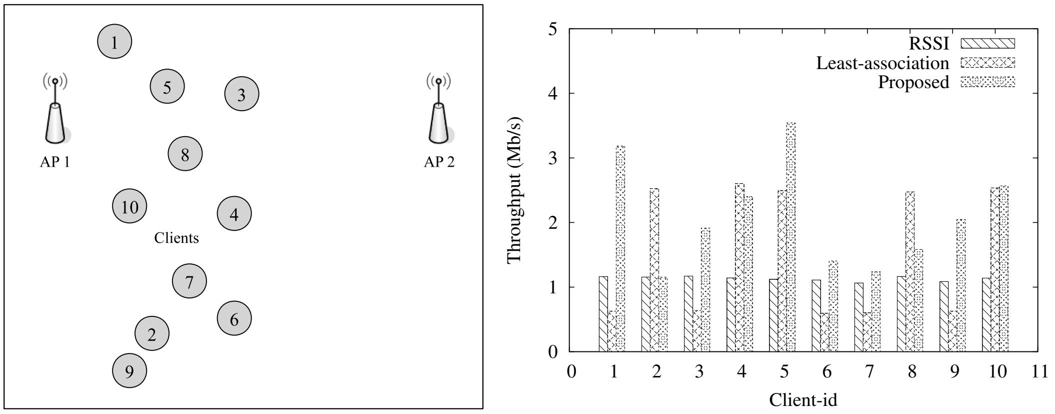
[2] The protocol overhead includes the DIFS interval, a backoff time, the SIFS interval, and an ACK transmission time.

TABLE II

Default simulation parameters.

| Parameter | Value |
|---|---|
| Propagation | Two-ray ground |
| Tx power | 24.49 dBm |
| Rx thresh | -67.54 dBm |
| Antenna height | 1.5 m |
| SNR thresh | 10 dB |
| CS thresh | -76.75 dBm |
| RTS/CTS | Disabled |
| Packet size | 1,000 bytes |



(a) Network topology

(b) Throughput of each client

Fig. 1. Network topology and throughput performance of each client.

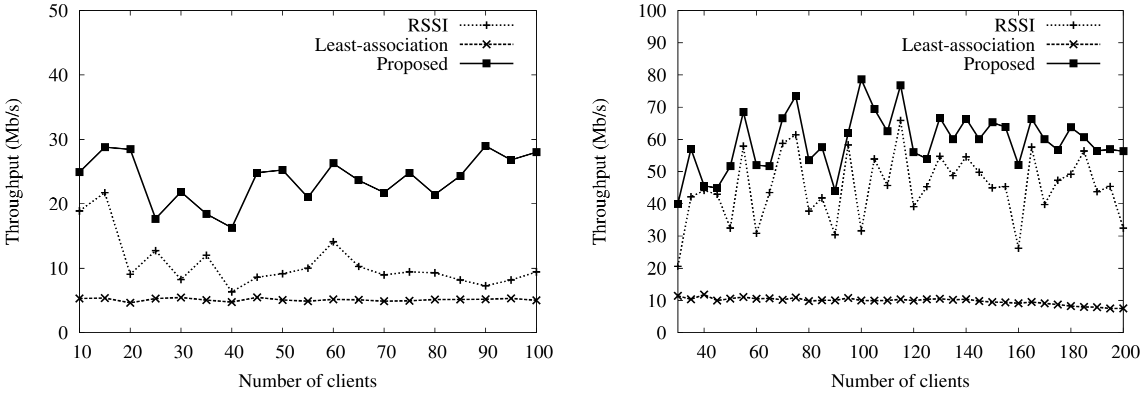
m. In this scenario, each client is able to associate with one of the two APs according to the criterion specified in the association algorithms.

Figure 1(b) shows the throughput results for each client offered by either of the two APs. In the RSSI scheme, all the clients are associated with only AP 1, which is closer to the clients, even though AP 2 has the capability to provide traffic. As a result, the aggregate throughput is lowest among the three schemes. The least-association scheme enables the clients to be evenly associated with AP 1 and AP 2. However, the throughput distribution of each client in this case is highly unbalanced because the clients that are located far away from AP 2 may be in association with AP 2 for the purpose of load balancing. The throughput performance of the proposed

TABLE III

Network throughput performance for the network topology shown in Fig. 1(a).

| Scheme | Throughput (Mb/s) |
|---|---|
| RSSI | 11.31 |
| Least-association | 15.72 |
| Proposed | 21.03 |



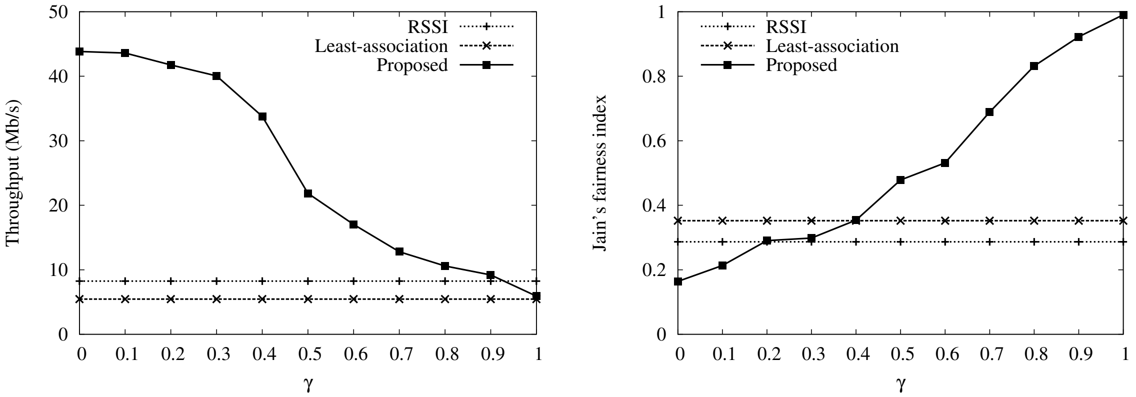
(a) Five APs

(b) Ten APs

Fig. 2. Throughput performance as the number of clients increases when there are (a) five APs and (b) ten APs.

algorithm is always higher than that of the RSSI scheme in all the clients. Compared with the least-association scheme, the proposed algorithm achieves the higher aggregate throughput, and the higher per-client throughput except the clients 2, 4, and 8. Note that throughput performance of the proposed algorithm could be further improved by adjusting $\gamma$ to a larger value.

Table III shows the network throughput performance, i.e., the aggregate throughput considering all clients, for different schemes. We observe that the network throughput achieved by the proposed algorithm is 33 % and 86 % higher than those achieved by the RSSI and least-association schemes, respectively. This result indicates that the proposed algorithm achieves the highest network throughput among existing association algorithms, while maintaining relatively high throughput performance for each client.



(a) Throughput

(b) Jain's fairness index

Fig. 3. Throughput and fairness performances with respect to the system parameter $\gamma$ when there are five APs and thirty clients.

### B. Random topology

We evaluated network throughput performance when all APs and clients were randomly and uniformly distributed. Figure 2 shows the network throughput performance with respect to the number of clients when there are five and ten APs. In the least-association scheme, since the clients are evenly associated with APs, each AP has the same number of clients, which have different transmission rates depending on their SINR. Because some low-rate clients that are located far away from the AP exist, the throughput performances of the APs with low-rate clients are significantly degraded due to the performance anomaly. Therefore, the least-association scheme shows the lowest network throughput performance, which is almost the same regardless of the number of clients. Because the RSSI scheme enables a client to be associated with the nearest AP, a client selects the AP that can transfer data with a high transmission rate. Thus, the throughput performance of the RSSI scheme is higher than that of the least-association scheme. Our proposed algorithm achieves the highest throughput performance among all three schemes because the association and traffic regulation for each client are performed for achieving high network throughput performance based on hybrid traffic allocation, in terms of the transmission rate and the number of clients.

Next, we investigated the effect of adjusting the system parameter $\gamma$ when five APs and thirty clients are randomly deployed. $\gamma$ is a key parameter for adjusting the performances of the equal-throughput and equal-airtime allocation policies. Figure 3(a) shows the network throughput curve with respect to $\gamma$. When $\gamma$ is zero, our proposed algorithm purely follows the equal-airtime allocation policy, resulting in the highest network throughput performance. The throughput gradually decreases as the network follows the equal-throughput allocation policy more closely. On the other hand, as shown in Fig. 3(b), the fairness performance gradually improves with respect to $\gamma$ as our proposed algorithm begins to follow the equal-throughput allocation policy more closely. Therefore, we conclude that there is a trade-off relationship between network throughput and fairness. When $\gamma$ is 0.4, our proposed algorithm can achieve the highest possible throughput along with the highest possible fairness, among all the association algorithms. Note that the optimal value of $\gamma$ may be different, depending on the number of nodes, data rate, and channel model in wireless networks.

## VI. Conclusion

In this paper, we focused on improving network throughput and fairness performances in multi-rate wireless LANs. We first presented two traffic allocation policies that are used in a single BSS network and proposed a hybrid traffic allocation algorithm on the basis of the trade-off relationship offered by the equal-throughput and equal-airtime allocation policies. We then proposed a network-wide association algorithm that allows a client to be associated with the AP that can provide the highest throughput improvement among multiple candidate APs while ensuring a certain level of fairness, and that enables the selected AP to regulate network traffic by executing the hybrid traffic allocation algorithm. The *ns*-2 simulations indicate that the throughput performance of the proposed algorithm is better than those of the RSSI and least-association algorithms. In future work, we plan to extend our hybrid traffic allocation algorithm to mobile client scenarios, in which client mobility causes a dynamic change of traffic loads.

## Appendix

*Proof.* First, we prove that the aggregate throughput $\mathcal{S}_a(C(a);\gamma)$ in Eq. (5) increases with $\gamma$. For $a \in A$, $\mathcal{S}_a(\gamma)$ is expressed as follows:

$$\mathcal{S}_a(\gamma) = \sum_{i=1}^{n} \{\gamma \cdot (s^{ET}(a,i) - s^{EA}(a,i)) + s^{EA}(a,i)\}. \tag{9}$$

By differentiating $\mathcal{S}_a(\gamma)$ with respect to $\gamma$, we obtain

$$\begin{aligned}\tfrac{d\mathcal{S}_a(\gamma)}{d\gamma} &= \sum_{i=1}^{n}(s^{ET}(a,i) - s^{EA}(a,i)) \\ &= \sum_{i=1}^{n}(\frac{1}{\sum_{j=1}^{n}\frac{1}{r(a,j)}} - \frac{r(a,i)}{n}) \\ &= \frac{n}{\sum_{j=1}^{n}\frac{1}{r(a,j)}} - \frac{\sum_{i=1}^{n} r(a,i)}{n} \leq 0, \end{aligned} \tag{10}$$

by the inequality of arithmetic and geometric means.

Second, we prove that the throughput fairness $F(a;\gamma)$ improves as $\gamma$ increases. We employ Jain's fairness index [31] as a fairness metric. It is expressed by

$$F(a;\gamma) = \frac{1}{n} \cdot \frac{(\sum_{i=1}^{n} s^{HA}(a,i;\gamma))^2}{\sum_{i=1}^{n} s^{HA}(a,i;\gamma)^2}, \tag{11}$$

where $s^{HA}(a,i;\gamma)$ is given by

$$s^{HA}(a,i;\gamma) = \gamma \cdot s^{ET}(a,i) + (1-\gamma) \cdot s^{EA}(a,i), \tag{12}$$

and the derivative of $s^{HA}(a,i;\gamma)$ with respect to $\gamma$ is given by

$$\frac{ds^{HA}(a,i;\gamma)}{d\gamma} = s^{ET}(a,i) - s^{EA}(a,i). \tag{13}$$

Next, we prove that the derivative of $F(a;\gamma)$ with respect to $\gamma$ is greater than or equal to zero, as follows:

$$\begin{aligned}\frac{dF(a;\gamma)}{d\gamma} &= \{\sum_{i=1}^{n}\frac{ds^{HA}(a,i;\gamma)}{d\gamma} \cdot \sum_{j=1}^{n} s^{HA}(a,j;\gamma)^2 \\ &- \sum_{i=1}^{n} s^{HA}(a,i;\gamma) \cdot \sum_{j=1}^{n}(s^{HA}(a,j;\gamma) \cdot \frac{ds^{HA}(a,j;\gamma)}{d\gamma})\} \\ &\cdot \frac{2\sum_{i=1}^{n} s^{HA}(a,i;\gamma)}{n \cdot (\sum_{i=1}^{n} s^{HA}(a,i;\gamma)^2)^2} \geq 0. \end{aligned} \tag{14}$$

Since $s^{HA}(a,i;\gamma) \geq 0$, we remove the last fractional term. Then, the remaining expression is given by

$$\begin{aligned}&\sum_{i=1}^{n}(s^{ET}(a,i) - s^{EA}(a,i)) \cdot \sum_{j=1}^{n} s^{HA}(a,j;\gamma)^2 \\ &- \sum_{i=1}^{n} s^{HA}(a,i;\gamma) \cdot \sum_{j=1}^{n}(s^{HA}(a,j;\gamma) \cdot \\ &\qquad (s^{ET}(a,j) - s^{EA}(a,j))) \geq 0. \end{aligned} \tag{15}$$

Let $y_i = s^{ET}(a,i) - s^{EA}(a,i)$ and $x_i = s^{HA}(a,i;\gamma)$. Then,

$$\sum_{i=1}^{n} y_i \cdot \sum_{j=1}^{n} x_j^2 - \sum_{i=1}^{n} x_i \cdot \sum_{j=1}^{n} x_j y_j \geq 0. \tag{16}$$

By modifying the above equation mathematically, we get

$$\sum_{i=1}^{n} y_i \cdot (\sum_{\substack{j=1 \\ j\neq i}}^{n} x_j^2) \geq \sum_{i=1}^{n} y_i \cdot (\sum_{k=1}^{i-1} x_k x_i + \sum_{j>i}^{n} x_i x_j). \tag{17}$$

From Eq. (17), we separate the $n$ number of inequalities with respect to $y_i$ for each $i$. By eliminating the $y_i$ terms on both sides of Eq. (17) and adding both sides of the expressions for the $n$ number of inequalities, we obtain

$$(n-1)\sum_{k=1}^{n} x_k^2 \geq 2\sum_{j>i}^{n}\sum_{i=1}^{n-1} x_i x_j. \tag{18}$$

Recall that for any two positive real numbers $x_i$ and $x_j$,

$$x_i^2 + x_j^2 \geq 2x_i x_j. \tag{19}$$

Thus,

$$\begin{aligned}
(n-1)\cdot\sum_{k=1}^{n} x_k^2 &= (x_1^2 + x_2^2) + (x_1^2 + x_3^2) + \cdots \\
&\quad + (x_{n-1}^2 + x_n^2) \\
&\geq 2(x_1x_2 + x_1x_3 + \cdots + x_{n-1}x_n) \\
&= 2\sum_{j>i}^{n}\sum_{i=1}^{n-1} x_i x_j.
\end{aligned} \tag{20}$$

□

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