AP Association in 802.11n WLANs with Heterogeneous Clients

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***Abstract*—As the latest amendment of IEEE 802.11 standard, 802.11n allows a maximum raw data rate as high as 300Mbps, making it a desirable candidate for wireless local area network (WLAN) deployment. In typical deployment, the coverage areas of nearby access points (APs) usually overlap with one another to provide satisfactory coverage and seamless mobility support. Clients tend to associate (connect) to the AP with the strongest signal strength, which might lead to poor client throughput and overloaded APs. Although a number of AP association schemes have been proposed for IEEE 802.11 WLANs in previous studies, none of them have considered the frame aggregation feature in 802.11n. Moreover, the impact of legacy 802.11a/b/g clients in 802.11n WLANS has not been considered in AP association. To fill in this gap, in this paper we explore AP association for 802.11n with heterogeneous clients (802.11a/b/g/n). We first formulate it into an optimization problem based on a bi-dimensional Markov model, aiming at providing clients with the bandwidth proportional to their highest physical data rates, and then propose two heuristic AP association algorithms that can efficiently make online decisions on AP association. We have also conducted extensive simulations and experiments to validate the proposed algorithms. Our simulation results show that under hotspot client distribution, the proposed algorithms can boost the throughput of 802.11n clients and overall throughput by 106% and 89%, respectively, compared to other AP association schemes. Experiments also confirm the effectiveness of the algorithms in enhancing aggregated throughput, maintaining proportional fairness among clients and balancing load among APs.**

Keywords: Wireless Local Area Networks (WLANs), IEEE 802.11n Standard, AP Association, Frame Aggregation, Heterogeneous Clients.

I. Introduction and Related Work

Recently, IEEE 802.11 based wireless local area networks (WLANs) have been widely deployed to provide pervasive Internet access. Typically, access points (APs) are deployed densely such that most of clients can be in the coverage areas of multiple APs. In conventional vendor implementations, a client selects the AP with the highest received signal strength indicator (RSSI) to associate with. However, due to the non-uniform distribution of WLAN clients, APs in the hotspots may become overloaded and the throughput of clients associated with such APs drops dramatically. Furthermore, the throughput of clients that are already associated with an AP will be severely affected by newly joined clients with lower data rates in multi-rate WLANs. Thus how to select an AP in a WLAN to balance load and guarantee high throughput for each client is a challenging issue.

On the other hand, the latest IEEE 802.11 standard, 802.11n, was ratified in 2009, introducing several new features, such as multiple-input multiple-output (MIMO), channel bonding, frame aggregation, etc. AP association becomes even more challenging in 802.11n WLANs, because a new dimension, the frame size, needs to be considered and the gap between the highest achievable data rate (300Mbps) and the lowest compatible data rate (1Mbps) is further widened. In this paper, we will consider AP association in 802.11n WLANs, with the objective of utilizing the physical data rate of each client to the maximum extent. In the following, we first review some existing AP association schemes for 802.11 and then discuss the new challenges introduced by 802.11n.

A. AP Association Schemes for WLANs

Since the conventional signal strength based AP association scheme may lead to imbalanced load and unfairness among clients, load balance has been the major objective of many proposed AP association schemes in the literature. In [1], it was proved that the objective of fairness and load balance in AP selection can be achieved simultaneously if one of them is achieved. Then based on this observation, the problem of AP selection was formulated into a max-min fair bandwidth allocation problem. The problem was shown to be NP-hard and an approximation algorithm was provided. In [2], a heuristic max-min throughput AP association scheme was proposed, in which the sum of the reciprocal of data rates from associated clients is used to estimate the load of an AP. It was pointed out [3] that greedy selection of the least-loaded AP does not guarantee optimum AP association, and the weighted sum of estimated throughput and achievable data rate is used as a metric in the proposed heuristic algorithm. Similarly, in [4] the ratio of RSSI and AP utilization is used as a measurement to define AP quality and the AP with the highest quality is selected. By using average packet delay as the load, an online least-load AP selection algorithm was presented in [5], with the convergence of the algorithm proved by game theory. In [6], the effect of hidden terminal was considered as the main reason of AP performance degradation. The difference between the measured and advertised channel utilization ratios caused by hidden terminals is defined as the load indicator, and the AP with the least load is selected in the algorithm. In [7], multiple channels were considered in AP association, in which a client first selects the APs that provide maximum data rate on each channel, then the AP that offers the highest rate-plus-throughput is associated.

However, the least-load AP association approaches in multi-rate WLANs discussed above may lead to reduced aggregated throughput. This is because that many clients are associated with distant APs for load balance, resulting in low data rates and throughput, while much higher data rates can be achieved by these clients even if associated with a relatively heavily-loaded AP. To balance client fairness and aggregated throughput, proportional fairness was considered for AP association in [8]. The AP association problem was formulated into a bandwidth allocation problem with the objective of maximizing the weighted sum of logarithm allocated bandwidth. Two approximation algorithms were proposed by relaxing the single association constraint. Simulation showed that the aggregated throughput could be enhanced by up to 2.3 times. Nevertheless, the algorithm is too complex to be deployed in WLANs.

B. Overview of 802.11n

In the latest IEEE 802.11n [9] standard, a data rate up to 300Mbps can be achieved with the introduction of several new physical layer technologies, such as multiple-input multiple-out (MIMO) antenna, orthogonal frequency division multiplexing (OFDM) and channel bonding (40Mhz channels) mechanism. To enhance MAC efficiency, a frame aggregation scheme is provisioned in IEEE 802.11n as well, in which multiple frames are aggregated into a single frame before transmission. In such a way, both the MAC overhead and random backoff period due to carrier sense multiple access with collision avoidance (CSMA/CA) are significantly reduced. In [10], an analytical model was formulated for 802.11n frame aggregation, from which the optimal aggregation size can be derived for different channel conditions and number of clients.

On the other hand, backward compatibility is kept in 802.11n to support conventional 802.11a/b/g clients. For convenience, we use *legacy clients* to refer to the conventional 802.11a/b/g clients in the rest of the paper. A high throughput mixed (HT-mixed) preamble or an explicit protection mechanism, such as RTS/CTS, or CTS-to-self, needs to be used by 802.11n clients at the presence of 802.11a/g and 802.11b clients, respectively. The performance of 802.11n clients with these preambles and protections was studied in [11]. It was shown that with the RTS/CTS protection, the MAC efficiency of 802.11n is only 12%, implying that most of time the wireless medium is wasted.

As shown in [12], in multi-rate WLANs, all clients tend to have the same throughput which is dominated by the client with the lowest data rate. This is because that with CSMA/CA medium access control, each client has an equal opportunity to access the medium in a long term, regardless of its data rate. The client with the lowest data rate needs the longest time to transmit a packet of the same length. It implies that the medium is occupied by the client with the lowest data rate most of time. In [13] it was shown that such performance anomaly also holds in 802.11n WLANs with legacy clients. A bi-dimensional Markov model for multi-rate WLANs proposed in [14] further validates this performance anomaly theoretically.

The problem of reduced aggregated throughput caused by least-load AP association algorithms becomes even more serious in 802.11n WLANs, due to the enlarged gap among data rates and frame aggregation. Take the 802.11n WLAN in Fig. 1 as an example, where clients 1, 2 and 3 are of 802.11g, 802.11b and 802.11n types, respectively. We assume that client 1 is already associated with AP a and client 3 is associated with AP b. By the RSSI-based AP selection approach, client 2 can be associated with either AP as the data rate is the same. By the least-load AP association approach, client 2 will associate with AP b, since the load of AP b is lower by using either the reciprocal of the data rate or average packet delay as the metric. However, much higher aggregated throughput can be achieved if client 2 is associated with AP a. The inefficiency becomes more evident when frame aggregation is enabled. Table I lists the throughput of each client and the entire network for different AP associations of client 2. From the table, we can see that the AP selection strategy in 802.11n WLANs has a significant impact on the throughput of 802.11n clients as well as the aggregated throughput. In [15], a joint

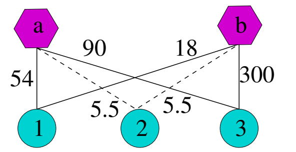


Fig. 1. An example WLAN. Nodes a and b are APs and nodes 1, 2 and 3 are clients. Lines denote the potential associations between APs and clients, and the numbers by the links are optimum data rates.

TABLE I
INDIVIDUAL AND AGGREGATED THROUGHPUT UNDER DIFFERENT ASSOCIATION STRATEGIES

AP for Client2	Client3 Frame Size	Throughput			
		Client1	Client2	Client3	Aggregate
AP a	1.5KB	3.9Mbps	3.0Mbps	21.0Mbps	27.9Mpbs
AP b	1.5KB	15.8Mpbs	3.0Mbps	5.6Mbps	24.4Mbps
AP a	30KB	15.8Mbps	2.8Mbps	53Mbps	71.6Mbps
AP b	30KB	3.9Mbps	3.0Mbps	180Mbps	186.9Mbps

channel assignment and AP association scheme was proposed for 802.11n WLANs, in which each client associates with the AP that leads to the highest aggregated throughput in the BSS. Nevertheless, this work mainly focused on the effect of channel bonding mechanism, leaving the impacts of frame aggregation and conventional 802.11a/b/g clients untouched.

In this paper, we consider AP association in 802.11n WLANs with heterogeneous clients to fully utilize the benefits of high data rates and frame aggregation capabilities of 802.11n clients, so as to enhance the aggregated throughput. We first develop a throughput estimation model for each client, and define MAC efficiency of clients accordingly. We then formulate the AP association problem into an optimization problem, aiming at maximizing MAC efficiency of clients proportionally. As the problem is very challenging to solve mathematically, we give two heuristic algorithms to minimize the impact of legacy clients on 802.11n clients. Finally, we conduct extensive simulations and experiments to evaluate the performance of the proposed algorithms. As will be seen from the test results, our algorithms perform significantly better than the compared schemes.

The rest of the paper is organized as follows. In Section II, we discuss the system model considered in the paper and give the problem formulation of AP association in 802.11n WLANs. In Section III, we present two heuristic AP association algorithms. We evaluate the performance of the proposed algorithms and compare them with other algorithms in Section IV. Finally, we conclude the paper in Section V.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

We consider a WLAN consisting of u 802.11n APs denoted by set A, and each AP has a limited coverage area. We assume that there are sufficient channel resources and frequency planning has been done ahead, thus each AP is assigned an interference-free channel.

There are n clients in the WLAN that are denoted by set N. We assume that all clients have saturated uplink traffic. For each client i, we define a variable $t_i \in \{0, 1, 2, 3\}$, to identify 802.11a, 802.11b, 802.11g and 802.11n clients, respectively. As 802.11a and 802.11b/g operate on different frequency bands, we will not consider 802.11a clients in this paper. We also define a variable L_i to denote the average data frame length for client

i. In addition, we use set R to denote all data rates supported by IEEE 802.11n standard. Since 802.1n standard is backward compatible, the supported data rates of 802.11a/b/g clients are a subset of R. By measuring the received signal strength of Beacon frames broadcast by an AP, each client can determine the transmitting data rate and bit error rate (BER) if associated with that AP. For each client-AP pair (i, a), we use $r_{i,a} \in R$ and $e_{i,a} \in [0, 1]$ to denote the transmitting data rate and BER of the pair, respectively. For simplicity, dynamic rate adaptation is not considered in this paper.

B. Association Model

For each client i, we use a variable $x_i \in A$ to denote its associated AP. If client i is not within the coverage area of AP a, the potential data rate $r_{i,a}$ would be zero. Thus the following condition needs to be met.

$$r_{i,a} > 0, \text{if } x_i = a \tag{1}$$

Then we simply use variables $r_i = r_{i,x_i}$ and $e_i = e_{i,x_i}$ to represent the data rate and BER between client i and its associated AP x_i, respectively. As aforementioned, 802.11n clients need to use HT-mixed preambles if they coexist with legacy clients. Moreover, protection mechanisms are required by 802.11g/n transmissions if 802.11b clients are associated with the same AP. Hence we define an operation mode variable o_a for each AP a to indicate the necessity of HT-mixed preambles and protections, which is defined as

$$o_a = \min\{t_i | \forall i \in N, x_i = a\} \tag{2}$$

C. Frame Transmission Time

Distributed coordination function (DCF) is used as the medium access control scheme in IEEE 802.11. With DCF, a client first listens to the medium for a DCF inter frame space (DIFS) period if the client has pending traffic. If the medium is idle during DIFS, the client selects a random backoff time from the contention window to postpone its transmission. In case the channel becomes busy again during the backoff period, the client stops counting down its backoff timer and waits for the channel to be idle. Otherwise, the client begins its transmission after the backoff period. If the data frame needs to be protected from legacy clients, the client first transmits a RTS or CTS-to-self frame. After that, the client transmits the data frame. A preamble is transmitted ahead of the data payload such that the receiver can acquire the coding and modulation schemes for the payload. After successfully receiving the data frame, the receiver sends back an ACK frame, beginning with a preamble as well, after waiting for a short inter frame space (SIFS) period. The timing of an 802.11 frame transmission is shown in Fig. 2. Thus, after obtaining the medium access opportunity, the required time for client i to successfully transmit a frame can be expressed as

$$\begin{aligned} T_s(i) = & T_{DIFS} + T_{prot}(i) + T_{pre}(i) + T_{SIFS} \\ & + T_{data}(i) + T_{SIFS} + T_{ack}(i) \end{aligned} \tag{3}$$

If a collision occurs, the required time for client i to detect the collision is

$$\begin{aligned} T_c(i) = & T_{DIFS} + T_{prot}(i) + T_{pre}(i) + T_{SIFS} \\ & + T_{data}(i) + T_{ack\ timeout}(i) \end{aligned} \tag{4}$$

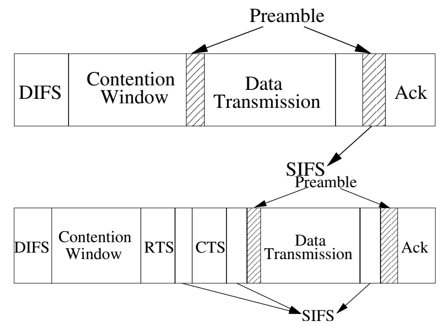


Fig. 2. Timing of an 802.11 frame transmission.

In Equations (3) and (4), T_{DIFS}, $T_{prot}(i)$, $T_{pre}(i)$, T_{SIFS}, $T_{data}(i)$, $T_{ack}(i)$ and $T_{ack\ timeout}(i)$ respectively stand for the DIFS duration, protection time, preamble time, SIFS period, data payload transmission time, ACK transmission time and ACK timeout time, where DIFS duration and SIFS duration are constants.

The protection time $T_{prot}(i)$ and preamble time $T_{pre}(i)$ of client i depend on its type and the operation mode of its associated AP. For 802.11b clients, the protection time is zero. The protection time of 802.11g and 802.11n clients is not zero if there exist 802.11b clients. The preamble time for 802.11b/g clients is fixed, while the preamble time of 802.11n clients depends on the operation mode of the associated AP. The numerical values of these times can be derived from the following equations.

$$T_{prot}(i) = \begin{cases} 0 & t_i = 1 \\ 0 & t_i = 2 \text{ or } 3,\ o_{x_i} = 2 \text{ or } 3 \\ 420us & t_i = 2 \text{ or } 3,\ o_{x_i} = 1 \end{cases}$$

$$T_{pre}(i) = \begin{cases} 192us & t_i = 1 \\ 20us & t_i = 2 \\ 28us & t_i = 3, o_{x_i} = 3 \\ 40us & t_i = 3, o_{x_i} = 1 \text{ or } o_{x_i} = 2 \end{cases}$$

$$T_{data}(i) = \frac{L_i}{r_i}$$

D. Throughput Estimation

In the bi-dimensional Markov model for multi-rate WLANs presented in [14], all clients are of the same type and associated with the same AP. In this subsection, we extend this model to support heterogeneous clients as well as multiple BSSs, to estimate the client throughput for making association decisions. We use m backoff stages in the Markov model to describe the exponential backoff behavior of DCF for retransmissions. At each back off stage l, the client randomly chooses a back off value from the contention window size, W_l, which can be derived as follows

$$W_l = \begin{cases} W_0,\ l = 0; \\ 2^l W_0,\ 0 < l \le m \end{cases} \tag{5}$$

where W_0 is the minimum contention window size at stage 0. Initially, a client is at back off stage 0. If the transmission fails, the client goes to backoff stage 1 and doubles its contention window size. The client transits back to stage 0 whenever the retransmission succeeds; Otherwise, the client goes to the next backoff stage. After retransmitting $m-1$ times, the client drops a frame and transits to stage 0. This state transition process for

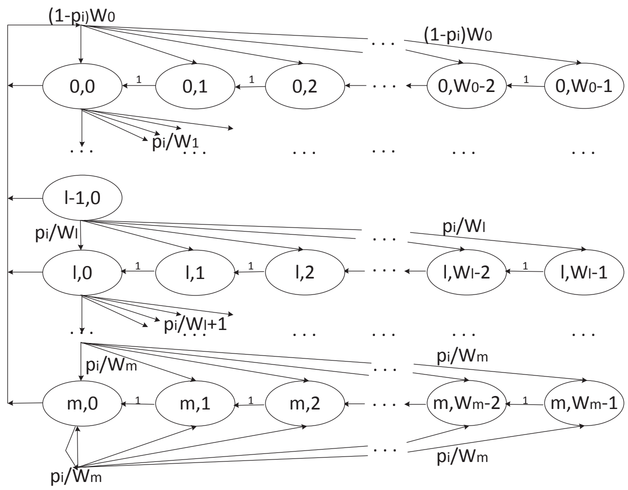


Fig. 3. Two-dimensional Markov chain model for client i with saturated traffic, where W_l is contention window size at state l and p_i is the transmission failure probability of client i.

client i can be expressed by the bi-dimensional Markov chain shown in Fig. 3. Let $s(t)$ and $c(t)$ be the stochastic processes of backoff stage and backoff counter for client i, then its stationary probability at state (l, k) would be

$$b_{l,k}(i) = \lim_{t\to\infty} P\{s(t) = l, c(t) = k\}, l \in [0, m], k \in [0, W_l - 1]$$

Assuming the transmission probability to be τ_i and the transmission failure probability to be p_i, the one-step transition probabilities of this Markov chain are

$$\begin{cases} P\{l,k|l,k+1\} = 1 & k \in (0, W_l - 2), l \in (0, m) \\ P\{0,k|l,0\} = (1-p_i)/W_0 & k \in (0, W_0 - 1), l \in (0, m) \\ P\{l,k|l-1,0\} = p_i/W_l & k \in (0, W_l - 1), l \in (1, m) \\ P\{m,k|m,0\} = p_i/W_m & k \in (0, W_m - 1) \end{cases} \tag{6}$$

According to the normalization condition for a stationary Markov chain, the summation of stationary probabilities for all states should equal 1, which can be formally expressed as

$$\sum_{l=0}^{l=m} \sum_{k=0}^{k=W_l} b_{i,k}(i) = 1$$

Using chain regularities and the one-step transition probabilities given in Equation (6), we can derive the stationary probability $b_{0,0}(i)$ at state $(0, 0)$ using the following equation

$$b_{0,0}(i) = \frac{2(1-2p_i)(1-p_i)}{(1-2p_i)(W_0+1) + p_i \cdot W_0(1-(2p_i)^m)}$$

The transmission probability τ_i for client i is equivalent to the summed probabilities that the counter equals zero at all backoff stages, that is,

$$\tau_i = \sum_{l=0}^{m} b_{l,0}(i) = \frac{2(1-2p_i)}{(1-2p_i)(W_0+1) + p_i \cdot W_0(1-(2p_i)^m)} \tag{7}$$

The probability that client i transmits a frame without colliding with other clients in the same BSS is equivalent to the probability that client i transmits while no other client is transmitting, which can be formally represented as

$$p_s(i) = \tau_i \prod_{j\in N, j\neq i}^{x_i=x_j} (1-\tau_j)$$

Similarly, the collision probability $p_c(i)$ for client i is equal to the probability that at least another client associated with the same AP of client i is transmitting, that is,

$$p_c(i) = \tau_i \cdot (1 - \prod_{j\in N, j\neq i}^{x_i=x_j} (1-\tau_j))$$

Besides collision, transmission failure can also be caused by channel error. For simplicity, we assume that the channel error probability of each bit within a frame is independent. Then the transmission failure probability due to channel error $p_e(i)$ can be derived from the bit error rate and average frame length of client i

$$p_e(i) = 1 - (1-e_i)^{8L_i}$$

Hence, the transmission failure probability for client i

$$p_i = p_c(i) + p_e(i) - p_c(i) \cdot p_e(i) \tag{8}$$

Thus, given an AP and its associated clients, the transmission probability τ_i and transmission failure probability p_i can be calculated by Equations (7) and (8) for all associated clients.

The theoretical throughput for client i can then be expressed as the length of successfully transmitted payload divided by the average duration of a time slot $T_{avg}(x_i)$ for all clients associated with the same AP, that is,

$$S_i = \frac{p_s(i) \cdot (1-p_e(i)) \cdot L_i}{T_{avg}(x_i)} \tag{9}$$

The average time slot $T_{avg}(a)$ for all clients associated with AP a can be further expressed as the summation of four expected slot durations

$$T_{avg}(a) = T_I(a) + T_S(a) + T_C(a) + T_E(a)$$

where $T_I(a)$, $T_S(a)$, $T_C(a)$ and $T_E(a)$ stand for the expected durations of an idle time slot, a successful frame transmission, a transmission failure due to collision, and a transmission failure due to channel error, respectively, for all associated clients.

The probability that all clients associated with AP a are not transmitting can be represented as

$$P_I(a) = \prod_{i\in N}^{x_i=a} (1-\tau_i)$$

Thus the average duration of an idle time slot in the BSS where AP a resides is

$$T_I(a) = P_I(a) \cdot \delta$$

where δ is the duration of a DCF backoff time slot.

The expected duration of a successful transmission for all clients associated AP a can be given by

$$T_S(a) = \sum_{i\in N}^{x_i=a} p_s(i) \cdot (1-p_e(i)) \cdot T_s(i)$$

Similarly, the expected duration of a transmission failure due to channel error for all clients associated with AP a is

$$T_E(a) = \sum_{i\in N}^{x_i=a} p_s(i) \cdot p_e(i) \cdot T_e(i)$$

where $T_e(i)$ is the duration of an erroneous transmission for client i. $T_e(i)$ is equal to $T_c(i)$, since a transmission error is not detected until the ACK times out.

To determine the expected duration of a collision for all clients in a BSS, we first sort all clients within the same BSS according to their collision duration T_c. Then we assume that client i may only collide with other clients that have a shorter collision duration. In other words, a collision between any two clients $i, j, (T_c(i) < T_c(j)$ would be counted by client j only, rather than both of them, when we calculate the expected collision duration of their BSS. Then the collision probability for client i is the probability that client i transmits and at least another client with a shorter collision duration transmits simultaneously, while all clients with a longer collision duration are not transmitting. Thus the collision probability for client i can be rewritten as

$$p'_c(i) = \tau_i \cdot (1 - \prod_{\substack{x_i = x_j \\ T_c(j) \le T_c(i) \\ j \in N, j \neq i}} (1 - \tau_j)) \cdot \prod_{\substack{x_i = x_j \\ T_c(j) > T_c(i) \\ j \in N}} (1 - \tau_j)$$

Then the expected collision duration for all clients associated with AP a is

$$T_C(a) = \sum_{i \in N}^{x_i = a} p'_c(i) \cdot T_c(i)$$

Finally, based on above equations, the estimated throughput for client i can be represented as

$$S_i = \frac{p_s(i) \cdot (1 - p_e(i)) \cdot L_i}{T_I(x_i) + T_S(x_i) + T_E(x_i) + T_C(x_i)}$$

E. Formulation of AP Association Problem

The objective of our AP association design is to ensure that the throughput of each client is proportional to the maximum supported data rate by all potential associations. To describe this, we define MAC efficiency α_i for client i

$$\alpha_i = \frac{S_i}{\max\{r_{i,a} | \forall a \in A\}}$$

We further define the utility function of client i as $\log \alpha_i$, then we can achieve proportional fairness among clients by maximizing $\sum_{\forall i \in N} \log \alpha_i$ [16]. We can now formally formulate the AP association problem for 802.11n WLANs into an optimization problem. Given a set of APs, a number of static clients, the physical data rate and BER for each applicable client-AP pair, we need to find an AP association assignment, such that the MAC efficiency of all clients is proportionally maximized. Using the constraints discussed in previous subsections, the AP association problem can be formulated as follows

Maximize

$$\sum_{\forall i \in N} \log \alpha_i$$

Subject to

$$x_i \in A, \forall i \in N \tag{10}$$

$$\tau_i = \frac{2(1 - 2p_i)}{(1 - 2p_i)(W + 1) + p_i \cdot W_0(1 - (2p_i)^m)} \tag{11}$$

$$p_i = p_c(i) + p_e(i) - p_c(i) \cdot p_e(i) \tag{12}$$

$$T_I(a) = \prod_{i \in N}^{x_i = a} (1 - \tau_i) \cdot \delta \tag{13}$$

$$T_S(a) = \sum_{i \in N}^{x_i = a} p_s(i) \cdot (1 - p_e(i)) \cdot T_S(i) \tag{14}$$

$$T_E(a) = \sum_{i \in N}^{x_i = a} p_s(i) \cdot p_e(i) \cdot T_E(i) \tag{15}$$

$$T_C(a) = \sum_{i \in N}^{x_i = a} p'_c(i) \cdot T_c(i) \tag{16}$$

$$S_i = \frac{p_s(i) \cdot (1 - p_e(i)) \cdot L_i}{T_I(x_i) + T_S(x_i) + T_E(x_i) + T_C(x_i)} \tag{17}$$

$$\alpha_i = \frac{S_i}{\max\{r_{i,a} | \forall a \in A\}} \tag{18}$$

In the formulation, constraints (11) and (12) specify the transmission probability and transmission failure probability for each client. Constraints (13), (14), (15) and (16) determine the expected duration of an idle slot, successful transmission, failed transmission due to channel error and failed transmission due to collision, respectively, for all clients associated with AP a. The estimated throughput and MAC efficiency for every client are given in constraints (17) and (18).

The above optimization problem is difficult to solve by mathematical tools for two reasons. First, there is an integrality constraint on x_i variables. Second, the problem is non-linear and non-concave. The complexity of this optimization problem grows exponentially as the network size increases. In the next section, we present two practical algorithms.

III. AP Association Algorithms

In this section, we present two randomized algorithms to provide practical solutions to the AP association problem in 802.11n WLANs. In the first algorithm, each client estimates the minimum MAC efficiency for each associable AP and associates with the AP leading to the maximum minimum MAC efficiency. In the second algorithm, APs are categorized by the type of associated clients. A client tries to associate with an AP that prefers its client type. The algorithms are described in detail in the following subsections. Since clients come and go randomly in their daily WLAN access, the proposed randomized algorithms can also be used as online algorithms.

A. Fair MAC Efficiency Algorithm

We first propose a randomized AP association algorithm, named *FAir Mac Efficiency (FAME)* algorithm, with the objective of maximizing the minimum MAC efficiency of all clients, so as to achieve proportional fairness among all clients. FAME uses the two-dimensional Markov model presented in the optimization formulation to estimate the potential throughput and the MAC efficiency for making association decisions. An AP maintains a MAC efficiency entry for every associated client, including the client type, the mostly used transmitting data rate, the average packet error rate, and the average frame payload size.

A client first estimates the potential data rate for each associable AP by passively measuring the RSSI of *Beacon* frames from all nearby APs. After obtaining the MAC efficiency entries from an AP, the client estimates the minimum MAC efficiency of all associated clients, including itself, if associating with that AP. The client then associates with the AP that leads to the maximum minimum MAC efficiency. The AP updates its list of MAC efficiency entries accordingly. As a client can be in the coverage of at most M APs and each AP has at most N associated clients, the time complexity of FAME algorithm is $O(MN)$, assuming that the time to estimate the minimum MAC efficiency of an AP is proportional to the number of associated clients.

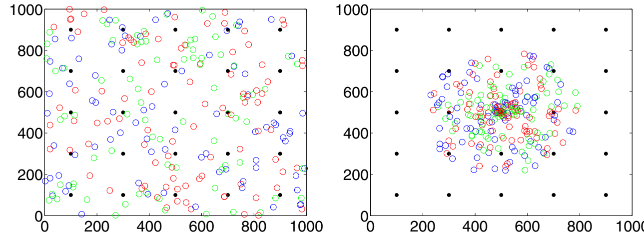
FAME algorithm can be easily implemented by extending the *Probe Response* frame of APs to include the list of MAC efficiency entries. This way a client can obtain the list of MAC efficiency entries of all associable APs and make an association decision by sending a standard *Probe Request* frame.

B. Categorized AP Association Algorithm

Noticing the fact that the throughput of 802.11n transmissions drops significantly when coexisting with legacy clients, we present another AP association algorithm in this subsection, named *Categorized algorithm*, to minimize the impact of legacy clients by associating different types of clients to different APs. APs are categorized by the type of their preferred clients. This algorithm is applicable in dense WLAN deployments, where every client is within the coverage of multiple APs most of the time. Thus a client is able to use satisfactory data rates by associating with a categorized AP, which does not necessarily have the best signal quality, while mitigating performance degradation due to transmission protection.

Initially, all APs are not assigned to any category. When client i joins the WLAN, it first checks whether it is within the coverage area of one or more APs that prefer the type of client i. If more than one AP qualify, client i associates with the AP leading to the highest data rate for the association. If there is no such an AP, client i examines whether it is covered by APs that have not been categorized yet. If so, client i associates with the AP resulting in the maximum data rate for the association and the AP updates its category to the type of client i. Clearly, it cannot be guaranteed that each client is able to associate with an AP with matched preference, especially when APs are deployed sparsely. In such a case, client i associates with the AP whose minimum data rate is closest to the data rate of client i if associated. The reason is that if the protection overhead caused by heterogeneous clients is inevitable, we want to minimize the data rate difference among all clients associated with the same AP. Similar to FAME algorithm, the complexity of Categorized algorithm is $O(MN)$.

Categorized algorithm can also be easily implemented by extending the *Beacon* frame of 802.11. In the Beacon frame, an additional category field and an additional lowest data rate field are appended. The lowest data rate field specifies the lowest transmitting data rate of all associated clients. After receiving Beacon frames from all associable APs, a client can make association decisions based on simple comparisons.



(a) Uniform (b) Hotspot

Fig. 4. An example of client distribution in the simulation. The black dots denote APs, and the circles denote clients. The different colors of circles represent different client types.

Because of the time varying nature of WLAN channel conditions and client activities, there could be better association opportunities for clients that have associated with their APs for a while. Both heuristic algorithms make new association decisions for these clients by disassociating them periodically. The updating frequency can be determined by the dynamics of the network.

IV. Performance Evaluations

In this section, we evaluate the performance of the proposed FAME and Categorized AP association algorithms via simulations and experiments, and compare them with the RSSI-based algorithm and the max-min throughput algorithm.

A. Simulation Results

We implemented the algorithms in the NS-2 simulator by adding multi-rate, multi-type and multi-channel support to the original 802.11 MAC module. As co-channel interference among basic service sets (BSSs) is not considered in this paper, we assign a unique channel to each AP to eliminate potential interference. The performance is evaluated in terms of client throughput, the MAC efficiency, the aggregated throughput, the MAC access delay and the AP load.

In the simulation, the WLAN is deployed in a $1000 \times 1000 m^2$ field and 25 APs are placed on a 5×5 grid evenly to ensure the entire field is fully covered. The transmission range is set to $250m$ and the applicable data rate for each client-AP pair is derived based on the RSSI, which in turn is calculated according to the two ray ground propagation model. The number of clients is set to 250 and the channel BER is fixed at $1e-5$. The type of each client is randomly chosen among 802.11b, 802.11g and 802.11n. As shown in Fig. 4, we consider two types of client distributions. (1) Uniform: all clients are randomly distributed over the entire field; (2) Hotspot: all clients are randomly distributed in a circle-shaped area with a radius of $300m$ and centered at the center of the field.

1) Client-Related Performance: We first evaluate the performance of the algorithms in the term of client throughput. To better illustrate the benefits of our algorithms, the throughput of different client types are plotted separately. Furthermore, the results for each client type are sorted and accumulated to exhibit the fairness among clients. The results for both uniform and hotspot distributions are plotted in Fig. 5.

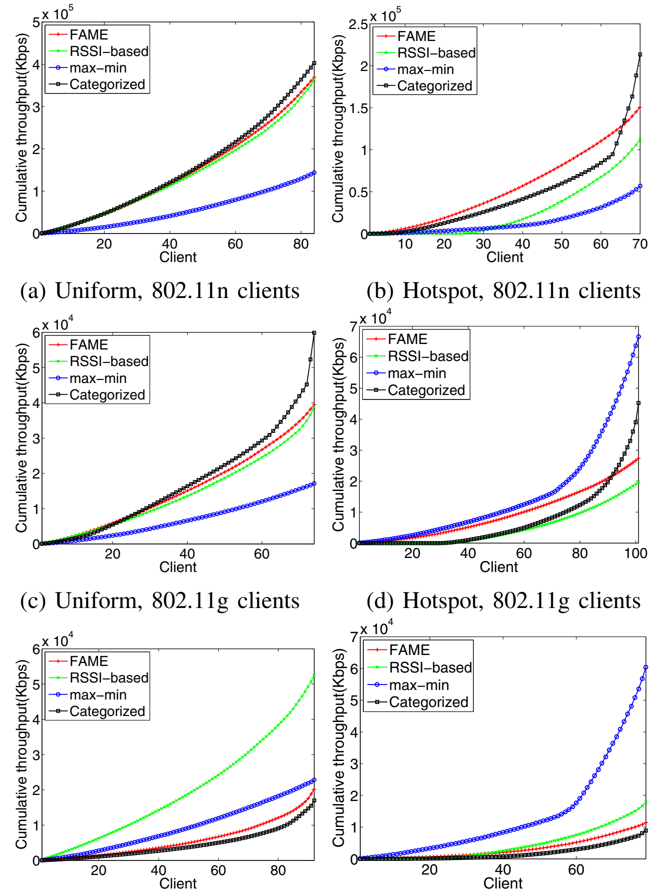
In uniform client distribution, the cumulative throughput of 802.11n, 802.11g and 802.11b clients are plotted in Fig. 5(a), (c) and (e), respectively. We can observe that for all 802.11n clients, the throughput of FAME and Categorized algorithm is higher than that of RSSI-based algorithm and max-min algorithm. For over 80% of 802.11g users, FAME and Categorized algorithms outperform the compared schemes. The throughput of 802.11b clients in FAME and Categorized algorithms is relatively lower than that in RSSI-based algorithm and max-min algorithm. This is predictable because we sacrifice the throughput of 802.11b clients purposely in the proposed algorithms, by associating them with APs that are at farther distances or with heavier load, to enhance the MAC efficiency of 802.11g/n clients and boost network throughput. Note that Categorized algorithm has a remarkable advantage over all other schemes for 802.11g/n clients and has acceptable performance for 802.11b clients, making it the most efficient algorithm for uniform client distribution.

Fig. 5(b), (d) and (f) exhibit the cumulative throughput of 802.11n, 802.11g and 802.11b clients with hotspot client distribution. It is notable that FAME algorithm performs better than other schemes by a large margin for all 802.11g and 802.11n clients. In addition, its performance for 802.11b clients is only slightly lower than that of RSSI-based algorithm and max-min algorithm. It validates that better performance can be achieved in 802.11n WLANs by taking the frame aggregation and protection overhead characteristics into AP association consideration. Furthermore, we can see that the cumulative throughput of all 802.11n or 802.11g clients in Categorized algorithm is even higher than that in FAME algorithm. However, similar to RSSI-based algorithm, the throughput of several clients is almost zero in Categorized algorithm. The reason is that as AP load is not considered in these two AP association algorithms, APs near the center of the hotspot may become severely overloaded, resulting in low performance for each associated client. Thus, FAME algorithm is the best candidate for WLANs with hotspot client distribution.

Fig. 5 also demonstrates the fairness among clients of the same type. We can observe that in both uniform and hotspot distributions, the cumulative throughput of each client type increases almost linearly in FAME algorithm and max-min algorithm. It indicates that channel capacity is fairly shared among all clients of each client type. On the contrary, the cumulative throughput of each client type grows relatively slowly at the beginning and faster near the end in Categorized algorithm and RSSI-based algorithm. Such phenomenon is more evident in the hotspot case. In other words, FAME algorithm is better than Categorized algorithm in terms of fairness among clients of the same type.

Next we examine the performance of the proposed algorithms by evaluating the MAC efficiency defined in Equation (13). The simulation results are plotted in Fig. 6, in which clients are grouped according to their client type, and for each client type, the clients are sorted in an ascending order of their MAC efficiency. We can see that except for 802.11b clients, the MAC efficiency of Categorized algorithm is better than that of other algorithms for most clients in the uniform case, while the MAC efficiency of FAME algorithm is higher than that of other algorithms for most 802.11g and 802.11n clients in the hotspot case. Note that the MAC efficiency in the uniform case is generally greater than the MAC efficiency in the hotspot case, as loads are distributed among all APs in the former case.

The aggregated throughput for each client type and all clients is given in Fig. 7. We can see that under uniform distribution, the aggregated throughput of 802.11n clients and all clients can be boosted by 11% and 9% respectively, compared with RSSI-based algorithm. Under hotspot distribution, FAME algorithm can boost the 802.11n throughput and the overall throughput by 106% and 89% respectively, compared with the max-min throughput algorithm.

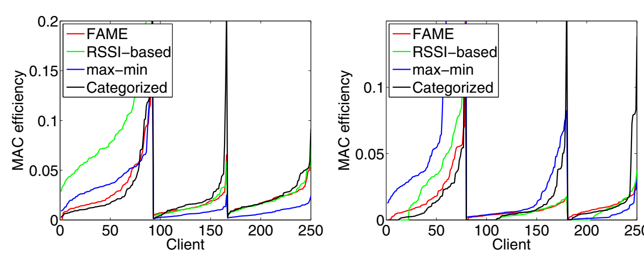


(a) Uniform, 802.11n clients (b) Hotspot, 802.11n clients

(c) Uniform, 802.11g clients (d) Hotspot, 802.11g clients

(e) Uniform, 802.11b clients (f) Hotspot, 802.11b clients

Fig. 5. Cumulative throughput of 802.11n, 802.11g and 802.11b clients under uniform client distribution and hotspot client distribution.

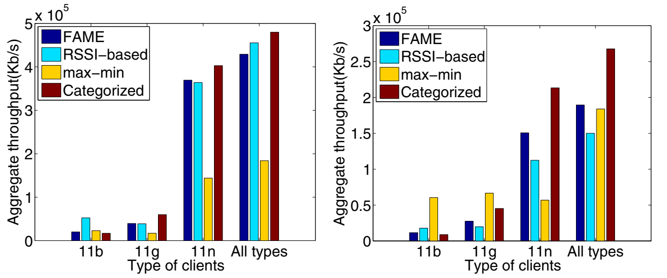


(a) Uniform (b) Hotspot

Fig. 6. Grouped MAC efficiency for all clients. The 802.11b, 802.11g and 802.11n groups are plotted from left to right. Within each group, clients are sorted in an ascending order of their MAC efficiency.

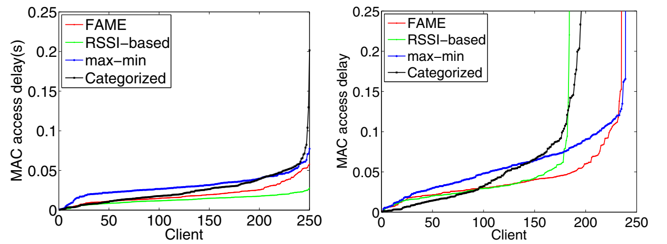
2) AP-Related Performance: In this subsection, we evaluate the proposed algorithms by studying two AP-related metrics: the average MAC access delay and the number of associated clients. The average MAC access delay for each client reflects the level of medium access competition, transmission overhead and transmission data rate. The number of associated clients reveals the load of an AP directly.

Fig. 8 shows the average MAC access delay for all clients. We can see that under uniform client distribution, RSSI has



(a) Uniform (b) Hotspot

Fig. 7. Aggregated throughput of each client type and the overall throughput for all AP association algorithms under both types of client distributions.



(a) Uniform (b) Hotspot

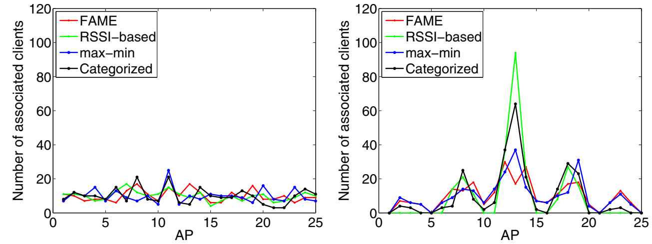
Fig. 8. Average MAC access delay of the algorithms under both uniform and hotspot distributions.

the shortest medium access delay, which can be attributed to its preference of high data rates and no overloaded APs. The MAC access delay of FAME is very close to that of RSSI for most clients, indicating the benefits of avoiding protection overhead when applicable. The presence of few relatively long delays in Categorized algorithm is due to the fact that some 802.11b clients have to transmit frames at the lowest data rate to far away APs due to categorization. The delay of the max-min algorithm is generally the highest as the features of 802.11n are not considered. Under hotspot client distribution, we can observe that FAME and max-min can avoid long delay for most clients by balancing the load among APs, and the delay of FAME is consistently shorter than the delay of max-min for the same reason as in the uniform case.

In Fig. 9, the number of associated clients for each AP is plotted. Note that under uniform distribution (Fig. 9(a)), the number of associated clients is very close to the average value of all the algorithms, although RSSI has a smaller variation. It is reasonable since the client distribution is the only factor impacting the load of each AP in that algorithm. On the other hand, as shown in Fig. 9(b), the load of RSSI and Categorized algorithm is not so balanced compared to other algorithms under hotspot distribution. However, the proposed algorithms still perform better in load balancing than other schemes.

B. Experimental Results

In this subsection, we verify the performance of the proposed algorithms by implementing and testing them in a testbed. As shown in Fig. 10, three 802.11n APs are deployed in two adjacent rooms as the testbed, with each AP operating on channel 1, channel 6 and channel 11 on 2.4Ghz frequency band, respectively. In addition, two 802.11b clients (indexed by 1 to 2), three 802.11g clients (indexed by 3 to 5) and five 802.11n clients (indexed by 6 to 10) are randomly placed in the two rooms. The wireless signal can penetrate the wall between



(a) Uniform (b) Hotspot

Fig. 9. Number of associated clients for each AP in the algorithms under both uniform and hotspot distributions.

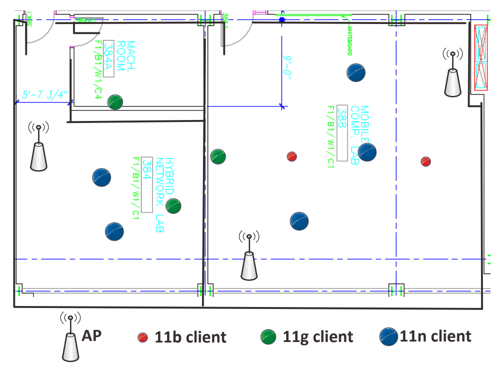
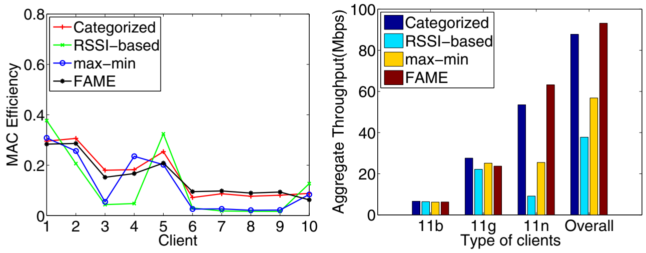


Fig. 10. Locations of APs and various clients for the 802.11n testbed.

the two rooms without obvious degradation. We run the test at midnight when no traffic is observed over the deployed WLAN of the building, thus external interference can be neglected. During the test, all clients transmit saturated UDP traffic to a PC, which is connected to all three APs via Gigabit Ethernet. We have two sets of test scenarios. The frame aggregation feature of 802.11n clients is disabled in one scenario and enabled in the other.

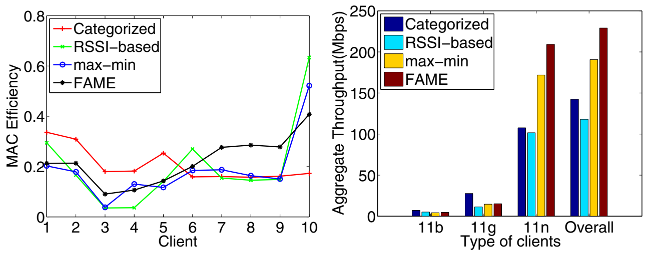
We first study MAC efficiency and aggregated throughput for all clients when the frame aggregation feature on 802.11n clients is disabled. The test results are shown in Fig. 11. We can see that by using the proposed AP association algorithms, the MAC efficiency of all clients is more balanced, especially for clients of the same type. Note that the MAC efficiency of 802.11n clients is much lower than 802.11b clients regardless of AP association algorithm, which is inevitable since without frame aggregation, 802.11n clients take much less time to transmit data payload, while their transmitting overhead at the MAC and physical layers is identical to or even higher than that of legacy clients. As for aggregated throughput, both the overall throughput and the 802.11n throughput are greatly improved by the proposed algorithms, since the protection overhead for 802.11n clients is completely avoided. Another interesting observation is that FAME provides higher aggregated throughput for 802.11n clients compared with Categorized algorithm. This is because that with FAME, 802.11n clients share APs with 802.11g clients, resulting in more balanced load among all APs, at the cost of slightly increased preamble durations for 802.11n clients.

We now evaluate the proposed algorithms when frame aggregation on 802.11n clients is enabled, which is the default option in reality. The MAC efficiency and aggregated throughput for all clients are plotted in Fig. 12 (a) and (b). Similar to the previous scenario, the proposed algorithms can bring more



(a) MAC efficiency (b) Aggregated throughput

Fig. 11. MAC efficiency and aggregated throughput for the testbed when frame aggregation of 802.11n clients is disabled.



(a) MAC efficiency (b) Aggregated throughput

Fig. 12. MAC efficiency and aggregated throughput for the testbed when frame aggregation of 802.11n clients is enabled.

balanced MAC efficiency among all clients. However, different from the previous scenario, we notice that the MAC efficiency of 802.11n clients is comparable to or even higher than that of legacy clients for all AP association algorithms this time. The reason is that 802.11n clients can transmit many data packets in each transmission by aggregating them into one 802.11 frame, although they have the same opportunity to access the medium as other clients and even need extra overhead to protect their transmissions. In contrast, legacy clients transmit one data packet in each transmission. Note that the MAC efficiency of a 802.11g client would be very poor if it shares the AP with 802.11b and 802.11g clients, because both 802.11b and 802.11n clients occupy the medium for much longer time for each obtained transmission opportunity. This is confirmed by the aggregated 802.11g throughput of the algorithms shown in Fig. 12 (b). Only for Categorized algorithm, the throughput of 802.11g clients is proportional to their data rates, whereby the medium is not shared with either 802.11b or 802.11n clients. Furthermore, 802.11n clients can achieve high throughput even if they share an AP with 802.11b clients, with the help of frame aggregation. For the overall aggregated throughput, FAME outperforms all other algorithms by minimizing the protection overhead for 802.11n clients, reducing the impact of 802.11n and 802.11b clients on 802.11g clients, and balancing network load at the same time.

From both simulation and experimental results, we can see that FAME algorithm leads to the best MAC efficiency fairness for all clients, while Categorized algorithm results in the highest aggregated throughput in dense WLAN deployments. On the other hand, Categorized algorithm takes less time to make association decisions than FAME algorithm, since it does not need to estimate the MAC efficiency of clients. As different control frames are used, both algorithms can be deployed at the same time. The most suitable algorithm can be activated according to application scenarios.

V. Conclusions

In this paper, we have studied AP association for IEEE 802.11n based WLANs with heterogeneous clients, in particular, addressed the new challenges introduced by the high data rates and frame aggregation mechanism of 802.11n. We considered the performance anomaly of 802.11n transmissions resulted from the associations of legacy clients, and formulated the AP association problem with heterogeneous clients into an optimization problem. We provided two AP association algorithms that can achieve high throughput by minimizing the impact of legacy clients on 802.11n clients. Finally, we conducted extensive simulations and experiments to assess their performance. Our simulation and experimental results show that not only high aggregated throughput, but also fairness and balanced load can be achieved by the proposed algorithms.

Acknowledgments

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References

[1] Y. Bejerano, S. Han and L. Li, "Fairness and Load Balancing in Wireless LANs Using Association Control," *10th ACM International Conference on Mobile Computing and Networking (MobiCom '04) ACM*, pp. 315-329, 2004.

[2] H. Gong, K. Nahm and J.W. Kim, "Distributed Fair Access Point Selection for Multi-Rate IEEE 802.11 WLANs," *5th IEEE Consumer Communications and Networking Conference CCNC*, pp. 528-532, 2008.

[3] G.S. Kasbekar, P. Nuggehalli and J. Kuri, "Online Client-AP Association in WLANs," *4th International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks*, pp. 1-8, 2006.

[4] N. Papaoulakis and C. Z. Patrikakis, "A Proactive, Terminal Based Best Access Point Selection Mechanism for Wireless LANs," *IEEE GLOBECOM Workshops*, pp. 1-4, 2008.

[5] O. Ercetin, "Association Games in IEEE 802.11 Wireless Local Area Networks," *IEEE Trans. Wireless Communications*, pp. 5136-5143, Dec, 2008.

[6] L. Du, Y. Bai and L. Chen, "Access Point Selection Strategy for Large-Scale Wireless Local Area Networks," *IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 2161-2166, 2007.

[7] T. Bonald, A. Ibrahim and J. Roberts, "The Impact of Association on the Capacity of WLANs," *7th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOPT)*, pp. 1-10, 2009.

[8] L. Li, M. Pal and Y. R. Yang, "Proportional Fairness in Multi-Rate Wireless LANs," *IEEE INFOCOM '08*, pp. 1004-1012, 2008.

[9] IEEE 802.11n Standard, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Enhancements for Higher Throughput,", *IEEE*, October, 2009.

[10] B. Kim, H. Hwang and D. Sung, "Effect of Frame Aggregation on the Throughput Performance of IEEE 802.11n," *IEEE WCNC*, pp. 1740-1744, 2008.

[11] T. Selvam and S. Srikanth, "Performance Study of IEEE 802.11n WLANs," *First International Communication Systems and Networks and Workshops (COMSNETS), 2009*, pp. 1-6, 2009.

[12] M. Heusse, F. Rousseau, G. Berger-Sabbatel and A. Duda, "Performance Anomaly of 802.11b," *IEEE INFOCOM*, pp. 836-843, 2003.

[13] V. Shrivastava, S. Rayanchu,J. Yoonj and S. Banerjee, "802.11n Under the Microscope," *8th ACM SIGCOMM Conference on Internet Measurement (ACM IMC '08)*, pp. 105-110, 2008.

[14] M. Laddomada, F. Mesiti, M. Mondin and F. Daneshgaran, "On the Throughput Performance of Multirate IEEE 802.11 Networks with Variable-Loaded Stations: Analysis, Modeling, and a Novel Proportional Fairness Criterion," *IEEE Trans. Wireless Communications*, 2010.

[15] M. Arslan, K. Pelechrinis, I. Broustis, S. Krishnamurthy, S. Addepalli, and K. Papagiannaki, "Auto-configuration of 802.11n WLANs," *7th ACM International Conference on Emerging Networking Experiments and Technologies (CoNEXT)*, 2010.

[16] F. P. Kelly, "Charging and Rate Control for Elastic Traffic," *European Transactions on Telecommunications*, vol. 8, pp. 33-37, 1997.