AP Association Optimization and CCA threshold Adjustment in Dense WLANs

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***Abstract*—Dense deployment of wireless local area networks (WLANs) is part of the next generation Wi-Fi and standardization (802.11ax) efforts are underway. However, dense deployment of WLAN access points (APs) faces increased interference and uncoordinated association of user stations (STAs) with APs, which degrade network throughput. To assess the potential of improving uplink throughput in the presence of interference using AP association coordination, we propose an association optimization algorithm that matches STAs to APs in dense WLAN (DWLAN). While existing cell breathing approaches suggest tuning of APs' beacon powers for association control, the proposed approach utilizes uplink signal-interference-noise ratio (SINR) of stations (STAs) to coordinate STA-AP association. In order to further coordinate interference and increase spatial reuse, an algorithm is proposed to adjust the clear channel assessment (CCA) threshold of the 802.11 MAC protocol in each AP cell to address the problem of overlapped basic service set (OBSS) that degrades overall network throughput. Performance evaluation reveals that our SINR-based AP association coordination and CCA threshold adjustment schemes achieve significant increase in per-user throughput in a DWLAN.**

***Index Terms*—wireless LANs, dense deployments, access points, optimal association, clear channel assessment**

I. Introduction

The growing need for wireless connectivity has prompted dense deployment of WLANs for outdoor, indoor, and/or enterprise access. Such dense deployment is also important for cellular-WiFi data offloading, especially in coverage areas with high concentrations of mobile users; for example, in stadiums, multi-tenant apartment buildings or in highly populated cities. Consequently, as more APs are closely deployed (usually 20 to 50-m spatial distance), the degree of contention among stations (STAs) and the interference level inevitably grow [1]. Dense wireless local area networks (DWLANs) guarantee coverage, performance degradation becomes severe with increase in interference and the number of contending STAs.

While high density of WLANs guarantees coverage, interference mitigation [1] and association control techniques [2], [3] are paramount to achieve better throughput. Since users are unevenly distributed, some APs experience saturation while others are lightly congested [2], necessitating new schemes for AP associations control in dense WiFi networks. Thus far, proposed techniques for capacity improvement include cell breathing [2], association control [3], [4], and clear channel assessment (CCA) adaptation [5]. While these approaches have achieved significant results, procedures to optimize STAs' association across APs while taking interference level at the APs into account are needed, especially in DWLANs.

The default strongest signal first (SSF) association in current 802.11 standards allows an STA to independently associate with an AP that offers strongest received signal strength (RSS) without considering the interference level or congestion at each AP, whereas high interference and congestion at an AP degrades performance. The cell breathing technique in [2] performs association control through reduction of an AP's beacon power. Reducing beacon power reduces AP cell coverage and forces some stations (STAs) to either associate with nearby APs or go out of coverage; cell breathing may therefore create coverage holes. In this paper, the problem of STA-AP association optimization is formulated as one of maximum weighted bipartite graph matching where the edge weights are the uplink SINRs of STA-to-AP links. Then the graph matching problem is solved using the Kuhn-Munkres assignment algorithm, to seek an optimized set of STAs-APs association to enhance performance. Following AP association optimization across the network, each AP and its associated STAs form the basic service set (BSS).

Another envisaged problem in DWLAN is related to the channel access mechanism. The 802.11 medium access method is a contention-based scheme known as carrier sense multiple access with collision avoidance (CSMA/CA) [5], [6]. The CSMA/CA mechanism requires that a node senses the channel through the CCA mechanism provided by the PHY before transmitting packets [6], [7], by sensing the current energy level in the channel. If the sensed energy is above the *CCA threshold*, transmission is deferred until the channel becomes idle. The CCA process could potentially degrade performance in DWLAN where AP cells usually overlap (for example, in multi-tenant apartment buildings where AP placements are usually unplanned), causing the problem of overlapped BSS (OBSS) [1]. Consequently, inter-BSS interference and transmission deferment become severe. To mitigate this problem, following AP association optimization, we determine per-BSS CCA threshold such that transmission in one BSS does not defer transmission in neighboring (or overlapped) BSS. Thereby increasing the number of simultaneous transmissions.

The contribution of this paper is to assess the potential throughput improvement from using SINR-based AP association coordination and per-BSS CCA threshold adjustment schemes. Our proposed AP association scheme is a centralized

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approach and it is mainly for performance evaluation in this paper. A distributed algorithm to realize this is beyond the scope of this paper and is a subject of ongoing research. By considering interference levels and congestion at APs when selecting an AP for an STA, performance ought to improve when compared with the default SSF association scheme; this is consistent with the work in [1], where the performance of an interference control scheme is documented. The paper is organized as follows: the preliminaries are presented in Section II. Section III contains the system model while the proposed optimal association and CCA threshold adjustment algorithms are discussed in Section IV. The performance evaluation on two scenarios of interest is presented in Section V, Section VI contains remarks on implementation while Section VII concludes the paper.

II. Preliminaries

A bipartite graph is used to model association (or matching) of STAs to APs in Figure 1, where the left vertices are related to the right vertices with edge weights. Let a bipartite graph $G = (\mathcal{N}, \mathcal{A}, \mathcal{E})$ in which $\mathcal{N}$ is a non-empty set of STAs on the left, $\mathcal{A}$ is the set of APs, and $\mathcal{E}$ is the set of edge weights such that $\mathcal{E} \subseteq \mathcal{N} \times \mathcal{A}$. Given edge weights, number of STAs $N = |\mathcal{N}|$ and $M = |\mathcal{A}|$ APs, each STA $i \in \mathcal{N}$ can be matched to exactly one AP, to obtain a match $\mathcal{M}$, which is a subset of edges $\mathcal{M} \subseteq \mathcal{E}$ connecting each vertex in $\mathcal{N} \cup \mathcal{A}$ such that each vertex in $\mathcal{A}$ is an endpoint of at least one edge in $\mathcal{M}$.

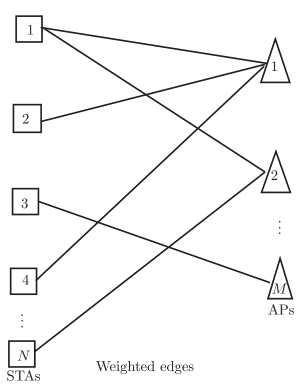

Fig. 1. Bipartite graph representation of a wireless LAN.

Consequently, a DWLAN is characterized by a network where each AP vertex is connected to at least one STA vertex in $\mathcal{N}$. The edge from STA i to AP j is weighted by w_{ij} representing the uplink SINR of STA i through AP j. This weight value varies as the number of APs within the STA's reception range changes and depends on the path loss model. Bipartite graph matching has been applied in different domains [8], [9]. Here, it is used to obtain a match that improves uplink throughput, using the semi-matching approach, which is a relaxation of the maximum bipartite matching problem [9]. A semi-matching is a subset of edges $\mathcal{M} \subseteq \mathcal{E}$ such that each vertex in $\mathcal{A}$ is an endpoint of at least one edge in $\mathcal{M}$, that is, each AP is an endpoint of at least one STA. Starting with a set of STA-AP SSF associations on a given DWLAN, the objective is to find an improved set of associations that enhances uplink throughput.

III. System and Network Model

In the WLAN model in Figure 1 a steady-state scenario is considered whereby all STAs are already present in the network and STAs are not leaving or/and joining the network dynamically. This corresponds to a *quasi-static* mobility pattern [3] of users, in which STAs stay within proximity of the network for a relatively long time. Prior to AP-STA association optimization, it is assumed that each STA has initially associated with an AP based on SSF association. With SSF association, the throughput at some APs may be degraded due to contention among STAs and the maximum traffic an AP can support decreases when an excessive number of active STAs are associated with an AP. For example in Figure 1, the degree of contention at AP_2 is lower than that at AP_1. As a result, the throughput at AP_2 could be higher by virtue of the shared medium by the fewer contending STAs. To improve network throughput, the proposed approach optimally matches the STAs to APs by considering the achievable SINRs.

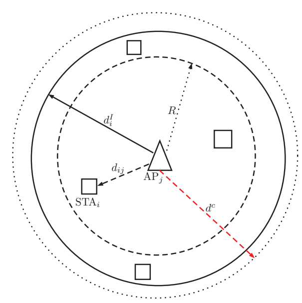

Fig. 2. AP deployment showing CCA sensing and interference ranges.

The edge weights of the bipartite graph in Figure 1 are the SINRs of STA-to-AP links. The received signal strength indicator (RSSI) in the IEEE 802.11 standard is used to measure the RSS of an STA [6], and with known interference and noise levels, SINRs can be estimated. For each AP that an STA detects within the carrier sensing range, there is a weight representing the SINR. For instance in Figure 1, STA_1 detects two (2) APs $\{1, 2\}$, resulting in weight vector $\mathbf{w}_1 = [w_{11}, w_{12}]$ for STA_1 indicating two possible associations for STA_1. Therefore, STA_1 will be matched to an AP by choosing w_{ij} from $\{\mathbf{w}_i, j = 1, 2, \ldots, M\}$ such that the SINR of STA_1 improves its throughput. Each STA i is spatially separated from AP j, and using a path loss model, the received power at AP j from STA i subject to propagation loss is:

$$P_{d_{ij}} = P_{tx} - PL_{d_o} + \delta \log_{10}\left(\frac{d_{ij}}{d_o}\right) \qquad (dBm) \qquad (1)$$

where P_{tx} is the transmit power (all STAs are assumed to transmit at the same power) and $P_{d_{ij}}$ is the received power at distance d_{ij} separating STA i and AP j, PL_{d_o} is the path loss at reference distance $d_o = 1$m and δ is the path loss exponent.

The coverage area of an AP is depicted in Figure 2, where interference range, d_i^I is approximated as [10]:

$$d_i^I = d_{ij}\left(\frac{1}{\frac{1}{\gamma_o} - \left(\frac{d_{ij}}{d_o}\right)^{\delta}\frac{N_o}{P_{d_{ij}}}}\right)^{\frac{1}{\delta}}, \qquad 1 \le i \le N, 1 \le j \le M, \tag{2}$$

where N_o is the background noise, γ_o is the SINR threshold defined for different data rates in 802.11 networks as shown in Table I. Any node transmitting within d_i^I interferes with STA i's uplink signal at receiver AP$_j$ provided the distance d_k between AP$_j$ and the interfering source k, $d_k \le d_i^I$. In this paper, the SINR γ_o of the highest supported data rate of 56Mbps in Table I is used to estimate the interference range for each AP receiver; this choice is used to evaluate performance under minimum interference or/and maximum system sensitivity specified in most 802.11 systems.

TABLE I
SINR REQUIREMENTS FOR RATES IN 802.11A/G WLAN [11].

Rate (Mbps), R_k	54	48	36	24	18	12
SINR, γ_o (dB)	24.6	24	18.8	17	10.8	9
Min. sensitivity, θ (dBm)	-65	-66	-70	-74	-77	-79

Due to the CSMA/CA protocol, only a subset of STAs can transmit concurrently in the uplink for a given transmission time. Out of these, $\mathcal{N}_i \subseteq \mathcal{N}$ might be interfering with the desired signal from STA$_i$ at the AP receiver. Let k represent an index of an STA in $\mathcal{N}_i$, i.e., STA$_k$ is at distance d_k from the AP receiver such that $d_k \le d_i^I$. The total interference on STA$_i$'s signal received at AP$_j$ can be written as:

$$\mathcal{I}^{ij} = \sum_{k \in \mathcal{N}_i, k \neq i} P_{d_{kj}} \qquad 1 \le i \le N, 1 \le j \le M, \tag{3}$$

where $P_{d_{kj}}$ is the power of an interfering signal received at AP$_j$ from an interference source k in $\mathcal{N}_i$ transmitting simultaneously with STA$_i$ and affecting STA$_i$'s signal at the AP. $P_{d_{kj}}$ is estimated using the path loss model in (1). The achievable throughput of a STA in 802.11 networks depends on its SINR. Constrained by the total interference in (3), background noise, N_o, and path loss model in (1), the achievable SINR of STA i through AP j is given as:

$$\gamma_{ij} = \frac{P_{d_{ij}}}{N_o + \mathcal{I}^{ij}}, \quad 1 \le i \le N, 1 \le j \le M. \tag{4}$$

Using CSMA, an STA or AP is able to sense the channel and detect any active transmission within the carrier sensing distance, $d^c = d_{ij}\left(1 + \gamma_o^{\frac{1}{\delta}}\right)$. The transmission distance, R, of an AP can be defined in terms of the lowest received power, P_R from a STA at $R = d_o\left(\frac{P_{d_o}}{P_R}\right)^{\frac{1}{\delta}}$, which corresponds to the cell radius. The carrier sensing scheme in WiFi mandates STAs to sense the channel before transmitting. If the channel is busy, they back off and defer transmission. For the STA to commence transmission, the interference level under negligible noise should satisfy CCA threshold, Γ:

$$\mathcal{I}^{ij} \le \Gamma, \qquad 1 \le i \le N, 1 \le j \le M. \tag{5}$$

Since WLAN uses CSMA, if the perceived interference exceeds Γ, any node attempting to access the medium will receive a "busy" signal and back off during the carrier sensing period. Therefore, to ensure that an AP can support an STA on its channel, STA i will only be matched to AP j with SINR satisfying the constraint in (5). With a known set of interfering sources, the throughput of STA i through AP j can be upper bounded based on Shannon capacity as:

$$\Upsilon_{ij} = \log_2\left(1 + \gamma_{ij}\right), \qquad 1 \le i \le N, 1 \le j \le M, \tag{6}$$

where γ_{ij} corresponds to SINR of STA$_i$, and the graph edge weight $w_{ij} \approx \gamma_{ij}$ by the measured RSSI value. Maximum weighted bipartite matching [8], [9] guarantees that the association algorithm selects edges that improves overall throughput.

IV. Proposed Optimal Association and CCA threshold Adjustment Schemes

In this section, we present the proposed SINR-based AP association coordination and CCA threshold adjustment schemes. First, the problem of finding a set of AP associations that enhances throughput is formulated in terms of a classical combinatorial optimization problem [9], which has been previously solved using the Kuhn-Munkres assignment algorithm [8]. Our AP association algorithm is presented in **Algorithm 1**, and assumed to be executed at a central controller with network-wide information about all STAs and APs; this network information is retrievable by harnessing IEEE 802.11k functionalities. Given $\{w_{ij} | i \in \mathcal{N}, j \in \mathcal{M}\}$, we can formulate the problem as a combinatorial problem as:

$$\text{maximize} \quad \sum_{j}^{M}\sum_{i}^{N} \Upsilon_{ij} x_{ij} \tag{7a}$$

$$\text{subject to} \quad \sum_{j=1}^{M} x_{ij} = 1, \forall i \in \mathcal{N} \tag{7b}$$

$$\sum_{j=1}^{M} \mathcal{I}^{ij} x_{ij} \le \Gamma, \forall i \in \mathcal{N} \tag{7c}$$

$$x_{ij} \in \{0,1\}, 1 \le i \le N, 1 \le j \le M, \tag{7d}$$

where the variables x_{ij} in constraint 7(b) ensure that each STA associates with exactly one AP; $x_{ij} = 1$ if STA$_i$ is associated with AP$_j$, and $x_{ij} = 0$ otherwise. The constraint in 7(c) indicates that the maximum interference or energy sensed on the channel during CCA is below the CCA threshold, Γ. At the initialization stage, **Algorithm 1** estimates the SINRs of all STAs to construct an $N \times M$ weight matrix, **W**, containing the uplink SINRs of N STAs through M APs on the WLAN. The association optimization begins in *Step 2* of **Algorithm 1** by performing the weighted bipartite matching using **Algorithm 2** with $G = (\mathcal{N}, \mathcal{A}, \mathcal{E})$ as the input graph.

In **Algorithm 2**, without using slack variables, φ in Equation (7) can be computed in $O\left(N^2\right)$ time, but using slack variables yields efficient computation with complexity $O\left(N\right)$ in search for an augmenting path [14], [15], [13]. With centralized execution of this algorithm, optimal association is achievable with polynomial complexity $O\left(N^3\right)$ on a WLAN with N STAs. Efficient implementation of the Kuhn-Munkres algorithm has been extensively discussed in the literature, e.g., [14] and [15] provide thorough details. When an optimum matching, $\mathcal{M}$ is obtained in *Step 2(c)* of **Algorithm 1**, the selected edge weight matrix maximizes uplink throughput.

Algorithm 1: : Optimal Association

Input : $G = (\mathcal{N}, \mathcal{A}, \mathcal{E})$, γ_{ij}, Γ
Output : Match $\mathcal{M}$ of N-STAs to M-APs, Υ_{ij}, $\forall i \in \mathcal{N}$, $j \in \mathcal{M}$.
1. Initialization:
  a. Set given SSF association as initial graph, G
  c. Estimate SINR γ_{ij} of STA$_i$ through AP$_j$
  d. Set $w_{ij} \leftarrow \gamma_{ij}$ and construct $N \times M = |\mathcal{N}| \times |\mathcal{A}|$ weight matrix $\mathbf{W}$:
    $\mathbf{W}\left(i,j\right) = \{w_{ij} \in \mathbb{Z} : \forall i \in \mathcal{N}, j \in \mathcal{A}\}$
2. Begin Association Optimization:
  a. Begin with an empty match, $\mathcal{M} \leftarrow \emptyset$
  b. Call **Algorithm** 2: perform $N = |\mathcal{N}|$ stages.
  c. Output matching, $\mathcal{M}$ and throughput Υ_{ij}

Algorithm 2: : Kuhn-Munkres Algorithm [13]

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1. Set dual variables α_i and β_j for set $\mathcal{N}$ of STAs and set $\mathcal{A}$ of APs: $\forall i \in \mathcal{N}, \alpha_i = 0$ and $\forall j \in \mathcal{A}, \beta_j = \min_i \left(w_{ij}\right)$.
2. Set an unmatched node $i \in \mathcal{N}$ as the root STA$_i*$ of a Hungarian tree.
3. Let $\mathcal{N}^* = i \in \mathcal{N}$ and $\mathcal{A}^* = j \in \mathcal{A}$ be two sets of covered nodes $i \in \mathcal{N}$ and $j \in \mathcal{A}$ in the Hungarian tree. If an augmenting path is found, Go to 5. If no augmenting path and the Hungarian tree keeps growing, Go to 4.
4. Modify the dual variables α_i and β_j using:

$$\varphi = \frac{1}{2} \min_{i \in \mathcal{N}, j \notin \mathcal{A}} \left(w_{ij} - \alpha_i - \beta_j\right)$$

$$\alpha_i \leftarrow \begin{cases} \alpha_i + \varphi & i \in \mathcal{N} \\ \alpha_i - \varphi & i \notin \mathcal{N} \end{cases}$$

$$\beta_i \leftarrow \begin{cases} \beta_j - \varphi & j \in \mathcal{A} \\ \beta_j + \varphi & j \notin \mathcal{A} \end{cases}$$

5. Flip the matched and unmatched edges along an augmenting path to augment the current matching, $\mathcal{M}_N = \left(\mathcal{M}_{N-1} - P\right) \cup \left(P - \mathcal{M}_{N-1}\right)$, where $\mathcal{M}_{N-1}$ is the previous matching at $N-1$ stage and P is the set of edges in the augmenting path.

After optimal association $\mathcal{M}$, each AP forms a contention domain known as its basic service set (BSS) depicted in Figure 3; a BSS consists of an AP and its associated STAs. By virtue of the WLAN contention mechanism, STAs in BSS$_1$ must defer to other STAs' transmissions within the same BSS and not to STAs in neighboring BSS. To ensure this, A CCA threshold is then determined for each BSS for sensing and contention. In **Algorithm 3**, the BSS cell-edge SINR ϕ and received power ϱ in BSS$_j$ are used to estimate the maximum allowed interference, which determines the CCA threshold, Γ_j for BSS$_j$. This mitigates the well-known hidden terminal problem and ensures that the user at the cell-edge having the lowest SINR can be supported while preventing interference at the AP's receiver through the MAC layer contention avoidance mechanisms (CSMA/CA). Therefore, in each BSS, **Algorithm 3** performs the CCA threshold adjustment for each supported data rate rather than a fixed or vendor dependent setting in hardware. Once Γ_j is determined, AP$_j$ broadcasts the new CCA threshold value to all STAs in its BSS.

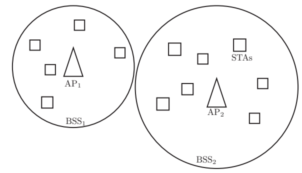

Fig. 3. WLAN basic service set of each AP.

Algorithm 3: : Per-BSS CCA Threshold Adjustment

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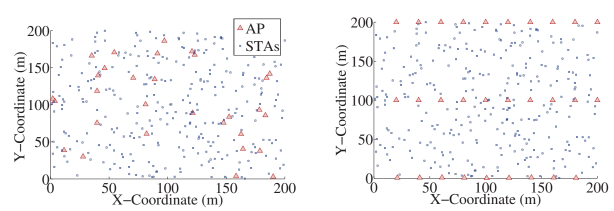
1. For each BSS$_j$, $1 \le j \le M$ in the resultant matching, $\mathcal{M}$:
2. Let ϕ be the lowest SINR in BSS$_j$.
3. Let ϱ be the received power of STA with the lowest SINR ϕ in BSS$_j$
4. Set γ_o to correspond to the SINR with the highest data rate R_k in Table I such that $\gamma_o \le \phi$.
5. Adjust the CCA threshold, Γ_j to support R_k for STA with SINR ϕ in BSS$_j$:
  $\Gamma_j = \left(\frac{\varrho}{\gamma_o} - N_o\right), 1 \le j \le M.$
6. AP$_j$ broadcasts new CCA threshold Γ_j to all STAs in BSS$_j$
7. All STAs in BSS$_j$ set their CCA threshold to Γ_j
8. Given Γ_j nodes compute carrier sensing distance d^c using (1).

V. Performance Evaluation

A. Test Scenarios and Simulation Setup

For the simulation, MATLAB 8.2 is used as the simulation environment to generate random network nodes and simulate the proposed algorithms and the CSMA/CA protocol. Our WLAN for evaluation consists of APs that are randomly deployed over an area of 200 $\times$ 200-m, and each AP is 20-m apart from the other for a deterministic densification realization. Table II summarizes the simulation parameters used. The STAs are randomly distributed at different locations resulting in topologies shown in Figure 4. The distance d_{ij} separating each STA i from each AP j and the corresponding received signal strength in dBm are measured. The deployment of STAs and APs in Figure 4(a) is referred to as experimental topology 1 (ET-1) corresponding to WLAN deployments found in multi-tenant apartment buildings, multi-office enterprise buildings, and campus locations where APs are not usually deployed in some regular patterns as in cellular networks.



(a) Experimental Topology 1 (ET-1): Randomly placed APs

(b) Experimental Topology 2 (ET-2): Regular AP pattern

Fig. 4. Generic network Topologies used for evaluation.

TABLE II
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Simulation network area	200m $\times$ 200m	Global CCA threshold, Γ	-60dBm
Number of APs $M = \|\mathcal{A}\|$	30	STA Transmit power (P_{tx})	15.85mW
Number of STAs $N = \|\mathcal{N}\|$	300	Background Noise, N_o	-90dBm
Pathloss exponent, δ	3.4 (ITU rush hour)	Receiver sensitivity	-65dBm
PCS	Enabled	Packet Size	1460 bytes

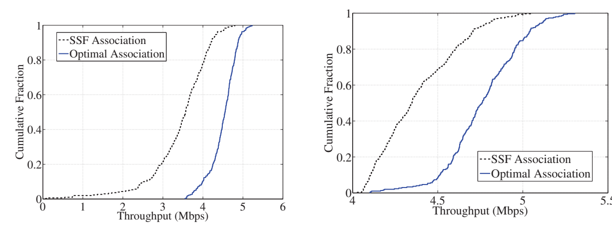
The second experimental topology (ET-2) in Figure 4(b) emulates a conference hall or an event auditorium with a large number of WiFi enabled devices. APs are uniformly spaced 20 m apart on the left, center, and right parts of the auditorium roof-top. In both ET-1 and ET-2, it is assumed that sufficient frequency planning has been performed and APs are deployed on the available orthogonal channels to avoid co-channel interference. The path loss exponent $\delta = 3.4$ is based on the ITU recommendation for "rush hour" propagation model [12]. Prior to using **Algorithm 1** for association optimization, it is assumed that all STAs independently associate with APs using the SSF association. Starting with this SSF association, **Algorithms 1** and **2** perform optimum association of STAs to APs using weighted bipartite matching.

The primary performance metric is the information theoretic throughput of the optimum association compared with that of SSF association. Another metric is the performance obtained by adjusting the CCA settings using **Algorithm 3** after the AP association is optimized. The achievable throughput using a fixed CCA threshold on the WLAN is compared to the throughput achieved when the CCA threshold is adjusted for each BSS based on its cell-edge SINR; this reveals the performance improvement of per-BSS CCA adjustment over the fixed CCA threshold setting.

In both the random (ET-1) and the regular (ET-2) topologies depicted in Figures 4(a), and 4(b) respectively, there are 300 STAs associated with 30 APs and all STAs transmit with a uniform power of 12 dBm (15.85 mW) and the noise power, N_o is set to -90 dBm. With the proposed optimal association algorithm, the majority of the STAs obtain best SINR when matched with an AP other than the one chosen using SSF association; this maximum weighted bipartite matching algorithm becomes efficient in dense 802.11 networks where STAs receive sufficient signal strength from multiple APs.

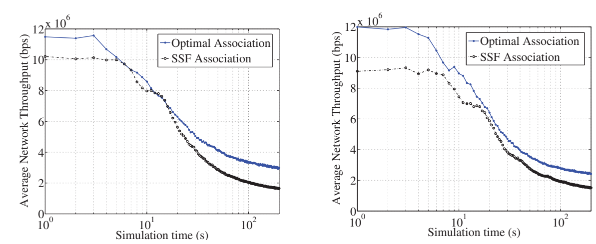
B. Numerical Results

The performance improvement of the proposed optimal association algorithm is measured using the rate determined by Eq. (6). Comparing optimal association with SSF association in both ET-1 and ET-2 topologies, Figures 5(a) and 5(b), respectively, show the cumulative distribution of STAs' uplink throughput and reveal significant performance improvement of the proposed optimal association over the SSF association. Figures 5(a) and 5(b) reveal that at least 90% of the STAs experience a significant increase in throughput. Examining the 10% level of STAs in Figure 5(a), about 54% (2.6 to 4 Mbps) performance gain in scenario ET-1 is obtained using the proposed AP association scheme over SSF association currently supported in 802.11 standards. Figure 5(b) shows STA throughputs in ET-2, and a more modest improvement of approximately 15% is observed at the $10th$ percentile of the cumulative distribution. Figures 6(a) and 6(b) show the average network-wide throughput over simulation time; throughput is improved for more than 90% of time in both random and regular AP placements.



(a) Experimental topology (ET-1) (b) Experimental topology (ET-2).

Fig. 5. Throughputs of all STAs using default SSF association versus optimal association with global CCA of -60dBm.

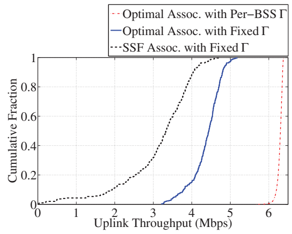


(a) ET-1 Network (b) ET-2 Network.

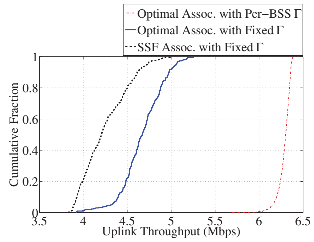
Fig. 6. Average network throughput of 300 STAs and 30 APs over simulation time using SSF association versus optimal association.

Next, we investigate the performance of CCA adjustment. Figure 7(a) depicts the performance of CCA adjustment based on **Algorithm 3** over a global fixed CCA setting in ET-1. Fig. 7(a) shows a further gain when optimal association is combined with CCA threshold adjustment. Looking at the 10th percentile of STAs, it is apparent that adjusting the CCA threshold in each BSS enhances STA throughput from 3.8 to 6 Mbps, which is an additional 58% gain. In the case of ET-2, when the CCA threshold adjustment is performed in addition to association optimization, the throughput at the 10th percentile of Figure 7(b), improves from 4.4 Mbps to 6.3 Mbps, which is a further 43% improvement.

Overall, the effect of combining AP association coordination with per-BSS CCA threshold adjustment yields approximately 130% gain in throughput in ET-1 and 66% gain in ET-2. We remark that a greater improvement is observed in



(a) ET-1 Network.



(b) ET-2 Network.

Fig. 7. Effect of per BSS CCA threshold adjustment over fixed global CCA threshold: cumulative distribution of uplink throughputs.

the random AP deployment ET-1 shown in Figure 4(a). This is likely due to the fact that in a regular topology (ET-2), APs cover most STAs' locations with sufficient SINRs and STAs are already connected to APs offering the best SINR.

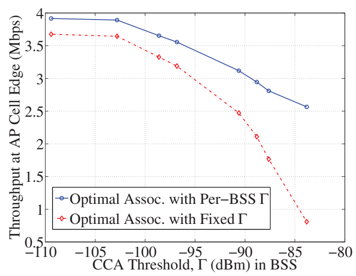


Fig. 8. Effect of per BSS CCA threshold adjustment on cell-edge STAs.

Lastly, Figure 8 shows that BSS cell edge throughput increases significantly when CCA threshold is calibrated using **Algorithm 3**. In Figure 8, we observed throughput at the cell-edge by selecting seven (7) STAs, each located at the cell-edge of different APs (or BSSs). We first observe their throughputs when the network-wide CCA threshold is fixed as -60dBm. Thereafter, the CCA threshold is adjusted per BSS using the SINR of STA at the cell-edge. The horizontal axis in Figure 8 shows the CCA threshold determined for each BSS, and the entire plot compares the cell-edge throughputs in fixed CCA case with per-BSS CCA threshold adjustment. It is apparent that there is a noticeable throughput enhancement at the cell-edges.

VI. Implementation Remarks

The centralized AP association coordination algorithm in this paper is not necessarily proposed as a recommended solution. Rather, it is intended for preliminary evaluation of an AP association scheme that is aware of interference at the APs. Since SSF association in itself is a distributed association scheme, work is ongoing on a distributed AP association that would be implementable for Wi-Fi systems. Nevertheless, the proposed AP association algorithm is implementable in cases where all APs belong to the same network operator with a central management system. The CCA threshold adjustment algorithm can be implemented independently at each AP because an AP could identify the cell-edge STA with the weakest SINR. Once the AP estimates the CCA threshold value for its BSS, its associated STAs can be informed of this threshold value using any of the available control frames in current 802.11 systems.

VII. Conclusion

Interference control is one of the approaches of the High Efficiency Wireless Study Group (HEWSG) to enhance per node throughput in DWLAN. Taking this as motivation in this paper, we have assessed the possibility of improving users throughputs in DWLAN using an SINR-based AP association coordination and per-BSS CCA threshold adjustment schemes. From our assessment, the numerical results show that considering interference at the APs when selecting an AP for association, enhances users throughputs in comparison with the default SSF association in current 802.11 standards. Also, using the cell-edge SINR to determine per-BSS CCA threshold further improves throughput when compared with the fixed CCA threshold setting in current 802.11 systems.

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