AP Selection for Downlink Throughput Enhancement in Dense IEEE 802.11 Networks

Phillip B. Oni, Student Member, IEEE and Steven D. Blostein, Senior Member, IEEE
Department of Electrical and Computer Engineering
Queen’s University, Kingston, ON, Canada.
Email: {phillip.oni, steven.blostein}@queensu.ca

Abstract

Enhancing downlink (DL) throughput is crucial because it is envisaged that in dense IEEE 802.11 networks, the majority of network traffic will be in the downlink especially in the emerging dense deployment of APs for cellular-WiFi offloading. Densification of IEEE 802.11 access points (APs) does not only increase the interference domain of each AP but also impairs the performance of downlink transmissions due to frequent back-offs created by the physical carrier sensing (PCS) portion of the carrier sense multiple access collision avoidance (CSMA/CA) channel access scheme. To address this issue, we propose AP selection algorithms to improve system throughput in the downlink. In the proposed algorithm, the AP selection process is distributed at the user stations (STAs) and is based on the estimated signal-interference-plus noise ratio (SINR) in the downlink. Based on simulated dense 802.11 networks, the proposed algorithms outperform the strongest signal first (SSF) AP selection scheme in current 802.11 standards as well as the mean probe delay (MPD) AP selection algorithm in [4]. While increasing STA densification, the proposed scheme is shown to increase DL throughput across the network.

Index Terms
wireless LANs, dense deployments, access points, clear channel assessment, AP selection

I. INTRODUCTION

The popularity of IEEE 802.11 or Wireless Fidelity (Wi-Fi) networks among users as a cheap data access network is increasing tremendously, and consequently, causing an increase in the number of access points (APs) deployed in places like residential/apartment buildings, hotels,
airports, campuses and enterprise buildings. The unprecedented demand for affordable high data rate and the emergence of bandwidth intensive applications is also a contributing factor. Similarly, the emerging cellular-WiFi offloading trend requires a high density of APs to handle the huge mobile data traffic [1]. With this promising solution to explosive mobile data traffic comes technical challenges that need to be addressed to boost the capacity of dense wireless local area networks (DWLANs).

Although densification of APs provides easy and affordable data access in homes, offices and campuses, it creates interference to neighboring APs especially in cases where AP cells overlap leading to overlapped basic service sets (OBSS) where inter-BSS or inter-AP or inter-cell interference becomes significant [2]. In addition to increasing AP’s interference domain, uncoordinated distribution of stations (STAs) among APs causes overwhelming channel access contention at overloaded cells due to the carrier sense multiple access collision avoidance (CSMA/CA) protocol specified in the IEEE 802.11 standard for channel acquisition. Interference, data collisions and congestion are major concerns in DWLAN. To this end, the goal of High Efficiency WLAN Study Group (HEWSG) on IEEE 802.11ax is to improve per-node throughput of DWLAN in the presence of interference sources [2].

The conventional AP selection procedure defined in 802.11 standard might cause a high degree of contention in some BSSs, and consequently degrades overall network throughput. Currently, the AP selection process in WLAN is based on the strongest received signal strength (RSS) or strongest signal first (SSF), a method whereby an STA selects AP that offers strongest RSS without considering interference, congestion and load at the candidate AP. Recent studies [3] - [9] focus on proposing new schemes for AP selection in 802.11 networks and demonstrate the inability of RSS-based scheme to guarantee the minimum system performance.

In [3] and [4], authors focus primarily on achieving fair distribution of STAs among APs to achieve load balancing as opposed to SSF AP selection scheme that has the tendency to cause load imbalances among APs [7]. The probe delay (PD) and mean probe delay (MPD) algorithms [4] select the AP with minimum probe delay. Similarly, an AP association control scheme is proposed in [5] to achieve proportional fairness. A graph matching approach to coordinate AP association and maximize uplink throughput is proposed in [6], where the links between STAs and APs are modeled as graph edges with uplink SINRs as edge weights. Using a channel measurement approach, the authors in [7] suggest that the hidden terminal problem and frame
aggregation are factors in selecting an AP that guarantees better throughput. Thus far, inter-BSS interference level at the target AP has not been considered.

The focus of this paper differs from the aforementioned AP selection schemes. Our goal is to improve data rates of downlink transmissions by associating STAs with APs that offer best SINR in the downlink. That is, improving throughput in dense WiFi networks when the AP with best downlink SINR (DL-SINR) is selected. Enhancing throughput in the downlink is important in DWLANs for two reasons. First, the majority of the traffic is in the downlink. Figure 1 depicts traces of bandwidth usage in a real-life residential Wi-Fi network with one AP and five (5) STAs, which reveals that the majority of Wi-Fi traffic is in the downlink. Taking video streaming as an example, after a user requests the service in the UL, the entire video streaming session occurs in the downlink.

![Fig. 1. Bandwidth usage for 27 days: download versus upload.](image)

Another motivation is that the problem of OBSS is inevitable, leading to severe inter-AP interference, which degrades performance in the downlink due close proximity of co-channel APs in dense deployments. Hence, there is need to improve DL throughput in the presence of inter-BSS interference. The proposed algorithm exploits awareness of interference in the downlink. The remaining parts of this paper is organized as follows. First, we present the system and network model in Section II. The proposed algorithms are presented in Sections III and IV while simulation results are presented in Section V and Section VI concludes this paper.
II. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, the system model for a DL (AP-to-STA) transmission is presented. In the downlink (DL) of a WLAN, APs transmit data to their respective associated STAs as shown in our system model in Figure 2. The achievable throughput in the downlink is of particular concern because the majority of dense Wi-Fi traffic will be in the downlink. On a typical DWLAN, let the set of APs be denoted as $\mathcal{A}$ serving a set $\mathcal{S}$ of STAs. Hence, the entire network consists of $M = |\mathcal{A}|$ APs and $N = |\mathcal{S}|$ STAs. For this downlink model, we will assume that all APs transmit at the same power $P^t$ (mW) and $d_{ji}$ ($\forall j \in \mathcal{A}, i \in \mathcal{S}$) is the distance between the transmitting AP$_j$ and the receiving STA$_i$ as shown in Figure 2.

Next, we describe channel contention in the downlink of 802.11 networks. The number of available orthogonal channels in Wi-Fi networks depends on the IEEE 802.11 standard being supported. For instance, the IEEE 802.11b/g standard supports 3 non-overlapping channels from the 14 available channels while IEEE 802.11a provides 8 non-overlapping channels. The more recent standard, IEEE 802.11ac, has two non-overlapping channels for 80MHz and one 160MHz non-overlapping channel. Therefore, due to an insufficient number of orthogonal channels for dense deployment of WiFi APs, many APs are deployed on the same channel and some BSSs overlap. Consequently, two or more APs contend for the same channel using CSMA/CA before...
transmitting in the downlink. For example, from Figure 2, AP_3 and AP_1 are co-channel APs within the carrier sensing range (CSR) of each other.

The CSR depends on the clear channel assessment (CCA) threshold used during the physical carrier sensing (PCS) process. PCS is usually performed within CSR to determine the presence of active transmissions on the channel. In order for an AP to detect the presence of an active AP on the channel, the energy level sensed during PCS is compared to the CCA threshold. The channel is occupied by another AP within the CSR if the sensed energy level is greater than the CCA threshold (e.g., Cisco recommends a −85dBm CCA threshold for dense deployments [10]). Therefore, with the PCS process in CSMA/CA, whenever AP_3 gains the channel for transmission, AP_1 remains silent; i.e., all co-channel APs do not transmit concurrently in the downlink.

For any supported 802.11 standard, let ω denote a channel belonging to the set of available orthogonal channels. Let us denote the set of co-channel APs on channel ω as A^ω and let A^ω^α represent the set of active APs (permitted by CSMA/CA to transmit) in A^ω on channel ω. By virtue of the CCA threshold, a subset of the active APs in A^ω^α will be in the contention domain (within CSR) of AP_j, ∀j ∈ A. Therefore, all active APs in the contention domain of AP_j form a set of co-channel APs with AP_j and this set is denoted as A^ω^j. This implies that AP_j will contend for the medium with other co-channel APs in A^ω^j, and if AP_j or any other AP in A^ω^j is transmitting on the channel, other APs remain idle in the downlink; mathematically:

\[ A^ω_j := \{ m ∈ A^ω^α, m ≠ j | λ > Γ, A^ω ⊆ A \}, j ∈ A, ω ∈ C \]  

where λ is the signal power sensed on channel ω during the PCS, C is the set of channels in any supported or chosen IEEE 802.11 standard. Interference coordination in the downlink of DWLAN is essential because deploying more APs does not necessarily translate to an increase in capacity, but will inevitably increase each AP’s contention domain.

Figure 2 illustrates a downlink interference scenario where AP_2 is outside the contention domain of AP_3. Therefore, a signal coming from AP_2 might interfere with downlink transmissions of AP_3 at receiver STA_2. From this scenario, the total interference at the receiving STA_2 in the downlink can be estimated depending on the number of APs transmitting outside the contention domain of AP_3 and whose signals are received by STA_2. Let A^I represent the set of APs interfering with the downlink signal of AP_j at receiver STA_i. The total interference received at
STA\textsubscript{i} from all interfering APs in $\mathcal{A}^I$:
\begin{equation}
I_{ji} = \sum_{z \in \mathcal{A}^I, i \in \mathcal{N}, j \in \mathcal{A} \setminus \mathcal{A}^I \cup \mathcal{A}^I \cap \mathcal{A}} P_{zi},
\end{equation}

where $P_{zi}$ is the received signal power at STA\textsubscript{i} from the $z^{th}$ interfering AP at distance $d_{zi}$ from the receiving STA\textsubscript{i}. This type of interference measurement is based on a one-time capture of the signal strength of an interference source. It does not account for the time variations of the wireless channel and the signal strength. Also, the frames received from different interfering sources vary in size and each interfering AP might use a different PHY rate for transmission. Therefore, using the passive interference measurement approach in [11], we can reformulate (2) to account for these variations as follows:
\begin{equation}
I_{ji} = \frac{1}{T} \sum_{z=1}^{\mathcal{|A}|} \sum_{k=1}^{K} \frac{P_{zi}L_{zi}}{R_{zi}}, \quad z \in \mathcal{A}^I, i \in \mathcal{N}, j \in \mathcal{A} \setminus j \neq z
\end{equation}

where $K$ is the number of frames and $L_{zi}$ is the length of each frame in bits received from $z^{th}$ interferer, $R_{zi}$ is the PHY rate (bps) at which each frame is received and $T$ denotes the measurement period, and can be a sufficient number of slot times for accurate estimation. As a result of interfering signal power received at STA\textsubscript{i} from APs outside AP\textsubscript{j}'s contention domain, the SINR of the link between AP\textsubscript{j} and STA\textsubscript{i}:
\begin{equation}
\Psi_{ji} = \frac{P_{rji}}{(I_{ji} + N_0)}W, \quad 1 \leq i \leq \mathcal{N}, 1 \leq j \leq \mathcal{M},
\end{equation}

where $P_{rji}$ is the received power from AP\textsubscript{j} at STA\textsubscript{i} over a distance, $d_{ji}$, $W$ is the system bandwidth. Using Shannon’s capacity, the DL PHY rate is upper bounded by:
\begin{equation}
\Lambda_{ji} = W \log (1 + \Psi_{ji}).
\end{equation}

III. AP SELECTION ALGORITHM

In this section, we discuss the proposed AP selection algorithm in Algorithm 1. The probe request and probe response frames defined in IEEE 802.11 standards are used to perform the interference measurement in the downlink. A typical STA\textsubscript{i} captures the beacon frames (through channel scanning) from all APs within range to determine the set of candidate APs, $\mathcal{A}^c_i$ and selects the best-serving AP. Let $\kappa$ be the set of APs within range of STA\textsubscript{i}. In Step 2, a typical STA\textsubscript{i} listens to beacon frames from all APs within range and sorts the RSSs of the beacon frames in decreasing order (Step 3) and selects the AP with best RSS to complete the SSF association.
The SSF association is important to ensure that all STAs can discover APs within range and have network access. This prevents starvation in cases when a STA cannot find the AP offering best SINR. Once SSF association is achieved by all STAs, the algorithm proceeds in Step 4 to create set $A^c_i$ of candidate APs for STA $i$ from the set of APs within range. An AP is added to $A^c_i$ if its RSS at STA $i$ satisfies the minimum receiver sensitivity constraint i.e., $P_{ji} > \theta$. The choice of $\theta$ depends on the minimum supported data rate on the network. For example, in a typical 802.11 network, to support a minimum data rate of 12 Mbps, the receiver sensitivity $\theta$ is -79 dBm (for successful reception). Subsequent to each STA obtaining the set of candidate APs, the channel measurement using probe request and response frames begins in Step 5.

**Algorithm 1: DL-SINR AP Selection Algorithm (DASA)**

1: **Initialization:** All STAs associate with AP offering best RSS
2: Typical STA $i$, $\forall i \in \mathcal{N}$ listen to APs’ beacon frames (In promiscuous mode)
3: STA $i$ captures RSS from APs within range:
   \[ P_{r1i} \geq P_{r2i} \geq \ldots \geq P_{r|\kappa|i} \]
4: for $j \leq |\kappa|$ (For each AP within range); $\forall j \in \kappa, \kappa \subseteq \mathcal{A}$
   - if $P_{ji} \geq \theta$; $\forall j \in \kappa, \kappa \subseteq \mathcal{A}, \forall i \in \mathcal{N}$
     - STA $i$ adds AP $j$ to set $A^c_i$ of candidate APs
5: for $j \leq |A^c_i|$ (For each candidate AP for STA $i$)
   - STA $i$ sends probe request frame ($p_{REQ}$) to AP $j$
   - while $T \leq n \times $ Slot time
     - AP $j$ replies STA $i$ with probe response frame ($p_{RES}$)
     - STA $i$ captures the power level (dBm) of $p_{RES}$ frame from AP $j$
     - STA $i$ estimates the interference power (dBm) arriving with $p_{RES}$.
6: Using (3), STA $i$ estimates the average interference power level (dBm) arriving with $p_{RES}$ frames from each AP $z \in \mathcal{A}^I$.
7: STA $i$ estimates DL-SINR from AP $j$, $\Psi_{ji}$ using (4)
8: STA $i$ sends ASSOC_REQ frame to AP $j$ offering best DL-SINR:
   \[ \Psi_{1ji} \geq \Psi_{2ji} \geq \ldots \Psi_{\kappa N} \]
9: AP $j$ replies with ASSOC_RES frame
10: STA $i$ associates or re-associates with AP $j$

The typical STA $i$ sends a directed probe request frame to each AP in $A^c_i$. To increase the accuracy of the interference measurement in Step 5, the algorithm requires that multiple $p_{RES}$ frames be received by STA $i$ over a specified period of time. To do this, we define a measurement period $n \times $ Slot time where $n$ is an integer. Due to the power constraint of most STAs and other low power devices e.g., WiFi-enabled Internet of things (IoTs), **Algorithm 1** requires that STAs send only one $p_{REQ}$ frame but informs candidate AP $j$ to send multiple $p_{RES}$ frames.
within \( n \times \text{Slot times} \). The \textit{RequestInformation} (\texttt{dot11RadioMeasurementActivated = true}) parameter of the MLME-Scan.request primitive \cite{12} defined for channel scanning in IEEE 802.11 standard (2012) can be used to inform a candidate AP \( j \) to send multiple \texttt{P_RES} frames.

On receiving the \textit{probe response frame} (\texttt{P_RES}) from AP \( j \), STA \( i \) estimates the DL-SINR based on the magnitude of captured interference power from other frames arriving concurrently with \texttt{P_RES}. Then, it sends association request (\texttt{ASSOC_REQ}) frame to the candidate AP that offers the best DL-SINR. The candidate AP responds with association response (\texttt{ASSOC_RES}) frame. This algorithm is easy to implement and does not require modification to 802.11 management frames (\texttt{P_RES}, \texttt{P_REQ}, \texttt{ASSOC_REQ} and \texttt{ASSOC_RES}). Also, the channel measurement capability needed to capture RSS and interference is available in 802.11k-enabled nodes.

IV. OPTIMAL AP SELECTION ALGORITHM

In Section \[ III \] we propose an AP selection scheme, which might not be optimal under SINR, receiver sensitivity and CCA threshold constraints. These three types of constraints are related to interference distribution across the network. In this section, the problem of AP selection to maximize downlink throughput is formulated as a constrained optimization problem to obtain an optimal set of AP associations that improve downlink performance. This objective is formulated as:

\[
\text{maximize} \quad \Lambda_{ji} x_{ij} \\
\text{subject to} \quad \sum_{j=1}^{M} x_{ij} = 1, \forall i \in \mathcal{N} \quad (6a)
\]

\[
\sum_{j=1}^{M} x_{ij} \geq 1, \forall i \in \mathcal{N} \quad (6b)
\]

\[
x_{ij} P_{ji}^r \geq \theta, \quad \forall j \in \mathcal{M} \quad (6c)
\]

\[
x_{ij} \Psi_{ji} \geq \gamma_o, \quad \forall i \in \mathcal{N} \quad (6d)
\]

\[
x_{ij} P_{ji}^c \leq \Gamma, \quad \forall i \in \mathcal{N} \quad (6e)
\]

\[
x_{ij} \in \{0, 1\}, i \in \mathcal{N}, j \in \mathcal{A}, \quad (6f)
\]

where \( P_{ji}^c \) is the total power sensed on the channel during PCS, \( \gamma_o \) is the SINR threshold, constraint \( (6b) \) ensures that each STA associates with one AP; \( x_{ij} = 1 \) if STA \( i \) is associated with AP \( j \) and \( x_{ij} = 0 \) if otherwise. \( (6c) \) is the receiver sensitivity constraint while \( (6d) \) and \( (6e) \) are the SINR and CCA threshold constraints respectively. An AP begins transmission if \( (6e) \) is
satisfied during carrier sensing. This occurs when the total interference power \( P_{ji}^{c} \) received from other interfering APs does not exceed \( \Gamma \). Therefore, \( P_{ji}^{c} = I_{ji} \) and SINR \( \Psi_{ji} \) is related to \( I_{ji} \) by (4). Therefore, any feasible \((\Psi_{ji},)_{i \in N, j \in A}\) that satisfies (6d) also satisfies (6e), hence, constraint (6e) becomes redundant. Similarly, since \( P_{ji}^{r} \) and \( \Psi_{ji} \) are also related by (4) and STA\( i \) selects AP\( j \) offering best SINR, i.e,

\[
j' = \arg \min_{j} I_{ji} \quad \forall j' \in A, j \in A, i \in N
\]

\[
j^* = \arg \max_{j} \Psi_{ji} \quad j \in A, i \in N,
\]

consequently, any feasible \((\Psi_{ji},)_{i \in N, j \in A}\) that satisfies (6d) also satisfy (6c) and renders (6c) redundant as well. Therefore, (6) can be equivalently expressed as:

\[
\text{maximize} \quad \Lambda_{ji} x_{ij} \quad (8a)
\]

\[
\text{subject to} \quad \sum_{j=1}^{M} x_{ij} = 1, \forall i \in N \quad (8b)
\]

\[
x_{ij} \Psi_{ji} \geq \gamma_{o} \quad \forall i \in N \quad (8c)
\]

\[
x_{ij} \in \{0, 1\}, i \in N, j \in A, \quad (8d)
\]

and by introducing set \( \lambda = (\lambda_{ji})_{i \in N, j \in A} \) of Lagrangian multipliers to dualize constraints (8b) and (8c), a partial Lagrangian form is obtained for Problem (8):

\[
\mathcal{L}(\lambda, x, \Psi_{ji}) = \Lambda_{ji} x_{ij} - \lambda_{ji} \left( \sum_{j=1}^{M} x_{ij} - 1 \right) - \lambda_{ji} (x_{ij} \Psi_{ji} - \gamma_{o}). \quad (9)
\]

The solution to (8) is given in Algorithm 2 where the problem is solved numerically using linear programming (LP). A typical STA\( i \) captures SINR from all APs within range, then sets \( \hat{\Psi} \) containing SINR through each AP and uses the Gurobi LP solver [13] to locally determine its association, \( x_{ij} = 1 \).

V. PERFORMANCE EVALUATION

This section presents the simulation methodology, scenario and results. To simulate a dense 802.11 network, a custom CSMA/CA simulation is implemented in MATLAB. For performance benchmarking, we compare OPASA and DASA with the SSF scheme in 802.11 standards and the state-of-the-art mean probe delay (MPD) AP selection algorithm in [4]. In this analysis, the proposed OPASA mainly serves as an optimal throughput benchmarking.
Algorithm 2: Optimal AP Selection Algorithm (OPASA)

1: initial state: SSF (Steps 1 - 6 of Algorithm 1)
2: STA sets $\hat{\Psi} = (\psi_{ji})_{j \in A}, x$
3: inputs: $\gamma = \min (\hat{\Psi})$
4: STA loads Gurobi LP Solver: $\hat{\Psi}$
5: STA solves problem (8) locally
6: return $x, (\Lambda_{ji})_{i \in N, j \in A}$
7: STA selects AP $j \iff x_{ij} \in x = 1$

| Parameter | Value | Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|-----------|-------|
| Simulation network area | $1000 \times 1000m^2$ | CCA threshold, $\Gamma$ | $-86$ dBm | PCS and RTS/CTS | Enabled |
| Slot time | $20\mu s$ | STA Transmit power | $15.85$mW | AP Transmit Power | $100$ mW |
| CCA Time | $15\mu s$ | Pathloss exponent $\alpha$ | $3$ | P_REQ and P_RES Frames | $20$ Bytes |
| SIFS | $10\mu s$ | Receiver sensitivity, $\theta$ | $-90.96$ dBm | Mean Packet Size | $1460$ bytes |

A. Simulation Setup and Parameters

Our simulated network emulates a random AP deployment where APs and STAs are deployed on an area of $1000 \times 1000$ m$^2$ as shown in Figure 3. This network consists of 400 STAs and 50 APs deployed on three (3) non-overlapping channels of IEEE 802.11b PHY on a 2.4GHz band. Three (3) APs in close proximity are each placed on different channels (1, 6 and 11) to reduce the effect of co-channel interference. All APs have identical coverage area of 50m radius and transmit with a uniform power of $100$mW (20dBm). Table summarizes other key parameters and the received power at STA from AP $j$ is measured using:

$$P_{r_{ji}} = P_{t} (\text{mW}).G_{ji}d_{ji}^{-\alpha} \text{ (dBm)},$$

where $G_{ji}$ is the channel gain characterized by an exponential distribution i.e. $G_{ji} \sim \exp (P_{t})$ to account for fading and shadowing effects and $\alpha$ is the path loss exponent.

For carrier sensing, the PCS is enabled with minimum and maximum contention window (CW) 32 and 1024 respectively, while request to send (RTS)/clear to send (CTS) frames are used to minimize the effect of the hidden terminal problem - a node does not transmit immediately after sensing the channel to be idle under PCS, it transmits the RTS frame and begins transmission of payload when the CTS frame is received. For the rest of our simulation, $\alpha = 3$ in (10).
because $\alpha < 3$ corresponds to a free space path, which is not realistic for dense environments where obstructions are inevitable. The distribution of RSSIs under SSF association is shown in Figure 4 with a minimum of $-90.96$ dBm and maximum of $-32.46$ dBm, which means that all STAs have coverage with basic PHY rate between 2 – 4 Mbps in our dense deployment scenario. Therefore we set the minimum receiver sensitivity $\theta = -90.96$ dBm (minimum RSS on the network).
For channel access coordination, the IEEE 802.11 MAC layer is implemented using distribution coordination function (DCF) with Slot-time of 20\(\mu\)s, short inter-frame space (SIFS) = 10\(\mu\)s and CCA time of 15\(\mu\)s. To emulate the asymmetric traffic requests in Wi-Fi networks, APs and STAs transmit packets of varying sizes (between 1400 to 1500 bytes) with a mean packet size of 1460 bytes while the MAC header, CTS/RTS frame and ACK frame sizes are 34, 14/20 and 14 bytes respectively as defined in the 802.11 standard. It is assumed that the P\_RES and P\_REQ frames have same size as the RTS since the RTS frame has the source and destination address fields. Packets arrive at each node’s buffer at an exponential rate with parameter \(\lambda = 1/\text{Slot-time}\).

B. Simulation Results and Performance Benchmarking

The primary objective of the proposed algorithms is to improve downlink throughput. Figure 5 depicts the sum of average achievable throughput for different network sizes. The duration of interference measurement in (3) is set as \(T = n \times \text{Slot time}\) with \(n = 1000\). For the MPD, the probe delay is measured for the same duration. From Figure 5 we can infer that under any network size, OPASA and DASA improve throughput. For instance, when the number of contending STAs is 300, DASA achieved 43.08\% (43.22 to 61.84 Mbps) and 99.36\% (31.02 to 61.84 Mbps) throughput gains over MPD and SSF respectively. While increasing network size, OPASA and DASA outperform existing MPD and SSF AP selection schemes as shown in Figure 5. Since, OPASA and DASA select AP with best DL-SINR, they improve the PHY rate of each AP-to-STA link, which consequently improve the average end-to-end throughput.

In Figure 6 the distribution of all STA throughputs is presented. Between 20th and 90th percentiles, OPASA obtains better throughput than DASA, MPD and SSF. Observing the 40th percentile, the performance of MPD over SSF fluctuates while DASA nearly achieves 2\(\times\) gain over both SSF and MPD. At the 90th of the same Figure 6 DASA maintains 5\(\times\) gain over SSF while achieving 96.6\% gain over MPD. Between the 95th and 100th percentile throughputs under MPD and DASA schemes converge. MPD will be best suited for delay intolerant transmissions.

Figure 7 illustrates the end-to-end throughput of each of the 400 AP-to-STA links versus frame sizes. The first observation in Figure 7 is that as the frame size becomes larger, the throughputs achieved under MPD and DASA converge. This is likely due to the fact that delay becomes a factor in transmitting more bits and since MPD chooses links with less delay, more bits are likely to traverse the links at the same rate in DASA. Although, both MPD and DASA significantly
outperform SSF, OPASA doubles the throughputs of DASA, SSF and MPD for frame size below and above 1485 bytes.

In Figure 8, the PHY rate under each algorithm is plotted against the MAC end-to-end throughput. While PHY rate depends on the channel quality parameters such as received signal power, interference level and noise, end-to-end throughput depends on MAC header size, PHY rate, frame size and slot-time. Obviously, OPASA and DASA improve PHY rate by selecting links with best SINR and consequently enhanced the MAC throughputs. Under the OPASA
scheme, the total PHY rate and MAC throughputs for 50 STAs are 112.1Mbps and 26.45Mbps respectively, DASA achieves 81.83Mbps and 11.15Mbps while MPD achieves 40.68Mbps and 8.77Mbps. In terms of MAC layer efficiency (ratio of MAC throughput to PHY rate), MPD achieves $\approx 21.6\%$ while DASA yields $\approx 13.4\%$; MPD achieves high efficiency because it minimizes delay at the MAC layer than OPASA and DASA.

Figure 9 depicts the mean frame delay versus network size. Here, frame delay is the cumulative
time from when a packet arrives at an AP’s buffer and AP contends for a channel, to successful reception of packet at the STA. For a small network size of 50 STAs, the delay is below 2ms for SSF, MPD, OPASA and DASA while for larger network size of 400 users, the mean delay is higher in SSF. For 400 STAs under SSF scheme, the average frame delay is nearly 9.19ms while DASA and MPD maintain delays of 5.7ms and 5.4ms, respectively. For lower network sizes (50 to 150 STAs), OPASA, MPD and DASA achieve nearly same performance in terms of delay, the slight superiority of MPD over OPASA and DASA becomes obvious when the network size increases from 200 to 400 STAs. This discrepancy is as a result of increased contentions among APs frequently trying to serve more STAs in the DL. Overall, in terms of throughput, OPASA and DASA outperform SSF and MPD.

VI. CONCLUSION

The problem of inter-BSS interference is inevitable in dense 802.11 networks and degrades throughput. In fact, selecting an AP with strongest RSS does not always guarantee highest throughput due to interference at the target AP. Enhancing downlink (DL) throughput is crucial as most WiFi traffic is in the DL and to reduce the effect of interference among basic service sets (BSS). This paper presents a new scheme for AP-UE association for the DL that takes the BSS interference into account. The proposed OPASA algorithm serves as the optimal throughput benchmark while the much simpler proposed DASA algorithm provides significant end-to-end
throughput improvement while still taking interference into account. Simulation results reveal that selecting the AP offering best SINR improves throughput. Through extensive simulation, the proposed OPASA and DASA algorithms are compared to the default SSF scheme used in current 802.11 standards and the MPD algorithm proposed previously; significant throughput gain is demonstrated over both the SSF and the MPD schemes.

REFERENCES

[1] K. Lee, J. Lee, Y. Yi, I. Rhee and S. Chong “Mobile data offloading: how much can WiFi deliver?,” in IEEE/ACM Trans. on Networking, vol. 21, no. 2, April 2013.

[2] K. Shin, I. Park, J. Hong, D. Har and D. Cho “Per-node throughput enhancement in Wi-Fi DenseNets,” in IEEE Comm. Magazine, vol. 53, no. 1, pp. 118 - 125, January, 2015.

[3] B. Yigal, H. Seung-Jae and L. Li(Erran) “Fairness and load balancing in wireless LANs using association control”IEEE/ACM Trans. on Networking, vol. 15, no. 3, pp. 560- 573, June 2007.

[4] J. C. Chen, T. C. Chen, T. Zhang, E. van den Berg “Effective AP selection and load balancing in IEEE 802.11 wireless LANs,” in Proc. IEEE Globecom 2006.

[5] L. Wei, W. Shengling, C. Yong, C. Xuizhen, X. Ran, A. A. Mznah and A. Abdullah “AP association for proportional fairness in multirate WLANs,” in IEEE/ACM Trans. on Net., vol. 22, no. 1, Feb., 2014.

[6] P. B. Oni and S. D. Blostein “AP association optimization and CCA threshold adjustment in Dense WLANs,” in Proc. IEEE Globecom 2015 Workshop on Enabling Tech. in Future Wirel. Local Area Net., 2015.

[7] K. Hong, et al. “Channel measurement-based access point selection in IEEE 802.11 WLANs,” in Pervasive and Mobile Computing, 2015.

[8] F. Xu, X. Zhu, C. Tan, Q. Li, G. Yan and J. Wu “SmartAssoc: decentralized access point selection algorithm to improve throughput,” in IEEE Trans. on Parallel Distrib. Sys., vol. 24, no. 12, Dec., 2013.

[9] G. Athanasiou, T. Korakis, O. Ercetin, L. Tassiulas “A cross-layer framework for association control in wireless mesh networks,” in IEEE Trans. Mob. Comput., vol. 8, no. 1, 2009, pp. 65 - 80.

[10] Cisco System, Inc. “Wireless LAN design guide for high density client environments in higher education,” 2011, U.S.A.

[11] A. Murad. “A new approach for interference measurement in 802.11 WLANs,” 21st Annual IEEE Int’l Symp. on PIMRC., 2010.

[12] IEEE/ANSI, “Part 11: Wireless LAN MAC and PHY Layer Specifications,” IEEE Std 802-11-2012, 2012.

[13] Gurobi, “Gurobi Optimization,” http://www.gurobi.com Accessed: March 2nd, 2014.