Access Point Selection for Multi-Rate IEEE 802.11 Wireless LANs

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***Abstract*—Access Point (AP) selection is an important problem in WLANs as it affects the throughput of the joining station (STA). Existing approaches to AP selection predominantly use received signal strength which does not take into account collisions and interference level at each STA. In this paper, we exploit the local channel occupancy of the joining STA as well as that of the AP in order to develop an AP selection algorithm that takes into account collisions, interference, and received signal strength. We use NS-2 simulations to demonstrate the effectiveness of our approach. For a random topology consisting of 16 APs and 40 STAs, we show that our approach increases average throughput of the joining STA by 207% as compared to the traditional signal strength based AP selection approaches when decisions made by the two algorithms are different, and by 5% for all trials regardless of whether join decisions are the same or different.**

I. Introduction

Wireless local area networks (WLANs) have gained increasing popularity due to their convenience, flexibility, and mobility as compared to traditional wireline infrastructure. As a result, WLANs are becoming the preferred technology of high-speed broadband access in homes, offices, and other hotspots such as coffee shops, shopping malls, and airports. Each WLAN access point (AP) forms a Basic Service Set (BSS), and multiple BSSs can overlap to form an Extended Service Set (ESS) to provide seamless handoff for stations (STAs). Due to the dense deployment of WLANs and the use of ESS to provide roaming services, it is common for STAs to have multiple available APs to choose from. In addition, nearby BSSs often experience inter-BSS co-channel interference due to the limited number of orthogonal channels. The MAC rate and throughput for different APs can vary significantly depending on the physical channel conditions and the interference level. An inappropriate AP selection typically leads to compromised service, thus it is imperative for an STA to identify and select the AP that provides the highest data rate to improve user experience.

AP selection policy is not specified in IEEE 802.11 standards. Currently the most widely used scheme is to select the AP with the strongest received signal strength. Stronger received signal implies that the wireless channel is in better condition and can potentially support higher MAC rates, resulting in higher throughput for STAs. While this strategy is straightforward and easy to implement with no modifications and overhead to existing standards, it is ineffective especially in hyper dense deployment scenarios where adjacent APs could use the same channel. For example, as shown in Figure 1, consider two nearby co-channel APs who cannot sense each other, and an STA denoted by “joining” within range of both APs. Assume without loss of generality, the “joining” STA is closer to AP 2 and hence experiences a higher received signal power from it as compared to AP 1. The traditional received signal strength based method would result in selecting AP 2, even though it could experience more interference and a lower throughput. It is clear from this example that choosing an AP with the strongest received power is not optimal for hyper dense deployment of WLANs, and that interference and collisions should also be taken into account when selecting an AP among multiple available APs.

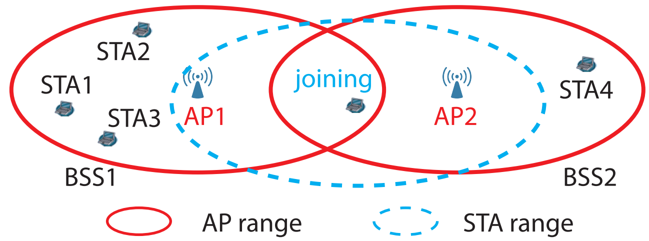

Figure 1. APs with Overlapping BSSs

To address these issues, a variety of schemes have been proposed in the literature [1]–[18]. Many work try to optimize potential throughput and bandwidth. Nicholson *et al*. propose that STAs quickly associate to each AP and run a battery of tests to estimate the quality of each AP's connection [1]. Vasudevan *et al*. propose to use potential bandwidth as a metric to facilitate AP selection [2], where beacon delays are used to estimate potential uplink (UL) and downlink (DL) bandwidth. Sundaresan *et al*. propose to optimize AP selection based on expected throughput obtained from cross-layer information [3]. Abusubaih *et al*. consider the effect of newly arrived STA on total network UL and DL throughput [4]. Similarly, Miyata *et al*. propose an AP selection algorithm to optimize total network throughput as well as preserving newly arrived STAs throughput [5]. Luo *et al*. consider wireless mesh networks and propose that a STA should make its association based on end-to-end performance [6]. Other work take interference and collision into account for selecting APs. For instance, Fukuda *et al*. propose to avoid interference when making AP selections [7]. Du *et al*. propose a metric to capture the effect of hidden nodes and multiple MAC rates [8]. They use the channel utilization field in the beacon packets and suggest that the difference between the AP's and the STA's respective channel usage captures the hidden node effect. Abusubaih *et al*. in a different work consider interference between BSSs and develop a metric based on collision probability to facilitate AP selection [9]. Jang *et al*. exploit the retry field in the MAC header to estimate collision probability, and propose to use expected throughput as a metric to choose APs [10]. Some researchers approach AP selection problem from fairness point of view. For example, Bejerano *et al*. propose to select AP for max-min fair bandwidth allocation [11]. Gong *et al*. further propose a distributed max-min throughput AP selection [12]. Zhou *et al*. consider multi-AP wireless hotspots and propose a new fairness notion called Fulfillment-based Fairness to select AP [13]. Judd *et al*. notice AP load imbalance problem for received signal strength based AP selection algorithm [14]. To alleviate this problem, Chen *et al*. propose to use probe delay to capture the load and probability of collisions on each AP [15]. They argue that higher load results in higher collision probability and therefore longer backoff time, so the probe frame delay increases when traffic load is heavy. Moreover, Bahl *et al*. propose to utilize the well-known cell breathing concept in cellular telephony to balance load in WLANs [16]. Other work try to study the AP selection problem using game theory tools. Musacchio *et al*. approach wireless AP selection from the economic point of view and model the problem as a dynamic game [17]. Mittal *et al*. present a game-theoretic analysis of wireless AP selection by selfish STAs [18].

In this paper, we propose a new AP selection algorithm that takes into account the inter-BSS interference with a more accurate collision estimation technique. We use the framework in [19] to estimate the collision probability for UL traffic at a given STA. The basic idea behind [19] is that all STAs and APs continually measure the spatial channel occupancy around them, with APs periodically broadcasting a compressed binary-valued busy-idle (BI) signal to indicate their local channel occupancy to all associated STAs. Each STA can then estimate UL collision probability by comparing its local BI signal with that of the AP's.

Motivated by [19], we propose a distributed AP selection algorithm to maximize a joining STA's DL expected true MAC rate. With information from APs' BI signals, we compute a metric at each joining STA to select the AP. This metric considers the multi-rate feature at the MAC layer as well as the inter-BSS interference and collisions.

In this paper, we use STA to refer to a non-AP station, and use *node* to refer to either an AP or an STA. The remainder of the paper is organized as follows: Section II discusses our packet loss model, and the method to estimate each component of packet loss; Section III describes our proposed algorithm; Section IV presents the performance evaluations, and Section V concludes the paper.

II. Packet Loss Modeling and Estimation

We categorize packet loss in WLANs into two classes: collisions and channel errors. A collision is defined as a packet failure at the intended receiver due to interference from other transmitters which are in close proximity to the receiver. A channel error is defined as an unsuccessful decoding of a packet due to low received SNR, which is caused by large path loss or deep multipath fade, given that the packet does not suffer from collisions. The probability of total packet loss can be expressed as:

$$P_L = 1 - (1 - P_C)(1 - P_e) \tag{1}$$

where P_C is the packet loss probability due to collisions, and P_e is the packet loss probability due to channel error given that the packet does not experience collisions. Equivalently, the packet success rate P_S is given by:

$$P_S = 1 - P_L = (1 - P_C)(1 - P_e) \tag{2}$$

In this paper, we assume none of the packets suffering from collisions are captured, and are therefore assumed to be lost.

Krishnan *et al*. proposed a framework to estimate UL collision probabilities at STAs, using the local channel occupancy at the STA as well as the periodically broadcasted BI signal associated with the STA's AP, which reflects the AP's local channel occupancy [19]. We now generalize the estimator in [19] to estimate the collision probability on link (Tx, Rx) as follows:

$$P_C(Tx, Rx) = f(BI_{Tx}, BI_{Rx}) \tag{3}$$

where BI_{Tx} and BI_{Rx} are BI signals collected at the transmitter and the receiver, respectively. For DL, suppose AP i is the Tx and STA j is the Rx, hence:

$$P_C(i, j) = f(BI_{AP_i}, BI_{STA_j}) \tag{4}$$

We classify collisions into three types: direction collisions (DCs), staggered collisions of type 1 (SC1), and staggered collisions of type 2 (SC2) [19]. A DC for a given node is a collision in which the node under consideration finishes its backoff period and starts transmitting at the same time as other nodes. An SC1 for a given node is a collision in which the node under consideration transmits first and is then interrupted by a hidden node. An SC2 for a given node is a collision in which the node under consideration interrupts the transmission of a hidden node. Intuitively, for the node under consideration, an SC2 occurs when another node is already transmitting to the intended receiver before the node starts to transmit, a DC occurs when another node starts transmitting at the same time the node starts to transmit, and an SC1 occurs when another node starts transmitting later than, but interrupts, the node's transmission. Based on the above description, $(1-P_C)$ can be expanded into [19]:

$$(1 - P_C) = (1 - P_{SC2})(1 - P_{DC})(1 - P_{SC1}) \tag{5}$$

where P_{SC2} denotes the probability of SC2, P_{DC} denotes the probability of DCs given that it does not experience SC2, and P_{SC1} denotes the probability of SC1 given that it experiences neither SC2 nor DC [19]. Due to the way collisions are counted, SC2 is the dominant type of collision for high traffic scenarios [19], and can therefore be used to approximate the total DL collision probability in a traffic-saturated WLAN network as:

$$P_C(i, j) \approx P_{SC2}(i, j) = \frac{\sum_t \mathbb{1}\{BI_{APi}(t) = 0, BI_{STAj}(t) = 1\}}{\sum_t \mathbb{1}\{BI_{APi}(t) = 0\}} \tag{6}$$

where $\mathbb{1}\{\cdot\}$ is the indicator function. The intuition is that this is the probability that the channel is busy at the STA given that it is idle at the AP, and hence if at time t a packet was transmitted by the AP when AP senses the channel to be idle, i.e., $BI_{APi}(t) = 0$, it would have experienced collision at the STA with probability $P_C(i, j)$.

An 802.11 packet uses PHY modulation rate R_{PHY} for preamble and PLCP header, and potentially higher modulation rates R_{MAC} for MAC frame. The probability of channel error for packets from AP i to STA j can be expressed as [20]

$$P_e(i,j) = 1-(1 - BER_{R_{\text{PHY}}}(SNR_{ij}))^{L_{\text{PHY}}} \\ (1 - BER_{R_{\text{MAC}}}(SNR_{ij}))^{L_{\text{MAC}}} \tag{7}$$

where L_{PHY} and L_{MAC} are the lengths of the preamble and PLCP header, and MAC frame, respectively. $BER_R(SNR)$ denotes the bit error rate which is assumed to be a known function of modulation rate R and SNR. SNR_{ij} can be estimated as:

$$SNR_{ij} = \frac{Pr_{ij}}{Noise} \tag{8}$$

where Pr_{ij} is the received power of beacon packets from AP i to STA j, and $Noise$ is the thermal noise that can be estimated from:

$$Noise(\text{dBm}) = -174 + 10\log_{10}(W) + N_f \tag{9}$$

where W is the bandwidth of wireless transmission, and N_f is the noise figure of the wireless system, which is a property of hardware. Substituting Equation (9) into Equation (8), SNR_{ij} can be estimated and consequently the channel error probability $P_e(i,j)$ can be computed as Equation (7).

With the estimates of collision probability $P_C(i,j)$ and channel error probability $P_e(i,j)$, the total loss probability $P_L(i,j)$ can be computed as Equation (1). We use $P_L(i,j)$ to estimate average backoff time if STA j associates with AP i, and to compute our proposed decision metric in Section III.

III. Proposed AP Selection Algorithm

In this section we describe an AP selection algorithm which takes into account both the MAC rate and the interference at the STA.

We begin by describing our system model. We assume WLAN operates in infrastructure mode with DCF, and hence no RTS/CTS is used. All traffic flows have the same priority, and packets have Poisson arrival whose rate depends on the application layer data rate. When serving packets, AP does not switch to a new packet until the previous packet is successful or dropped due to its retransmission limit being exceeded. The network is assumed to be saturated, i.e., APs always have backlogs in their queues. The MAC rate is determined by the path loss from an STA to its serving AP, and no rate adaptation is assumed to be used. In this analysis we assume APs to be on the same channel, and focus on one STA j joining the network while all other STAs are already associated to and exchanging traffic with their desired APs. For ease of notation, we use $P_C(i)$, $P_e(i)$ and $P_S(i)$ in place of $P_C(i,j)$, $P_e(i,j)$ and $P_S(i,j)$, respectively, since only one joining STA j is considered.

In our proposed algorithm, both APs and the joining STA record their BI signals at a resolution of $10\mu sec$ as suggested in [19]; this sampling period provides a good balance between estimation error and transmission overhead. APs broadcast the BI signals every $3sec$ with the overhead to send BI signal being about 3% in the 802.11b network. Before associating to any AP, the joining STA stays idle and records its local BI signal for the first $3sec$.

Our approach to AP selection is to maximize expected true MAC rate ($eTMR$):

$$AP_{sel} = arg\max_{i\in\mathcal{A}}(eTMR(i)) \tag{10}$$

where $\mathcal{A}$ is the set of candidate APs that the joining STA can choose from. In doing so, we consider both the potential MAC rate from an AP and the collisions due to inter-BSS interference. We define $eTMR(i)$ from AP i to the joining STA j as successful number of MAC payload bits transmitted over the time that AP i spent for delivering those data, including packet transmission time and all associated overhead time. $eTMR(i)$ is given by:

$$\begin{aligned} eTMR(i) &= \frac{\text{total successful MAC payload in bits from AP } i}{\text{total time to send MAC payload by AP } i} \\ &= \frac{\sum_k L_i(k) \times \mathbb{1}\{A_i(k)\}}{\sum_k t_i(k)} \end{aligned} \tag{11}$$

where $L_i(k)$ is the MAC payload size in bits from AP i on the kth transmission, $t_i(k)$ is the time that AP i spent on the kth transmission including both the MAC overhead and the payload transmission time, $A_i(k)$ is the event that the kth packet sent by AP i to the joining STA is successful, and $\mathbb{1}\{\cdot\}$ is the indicator function defined by:

$$\mathbb{1}\{A_i(k)\} = \begin{cases} 1 & \text{if the } k\text{th packet sent by AP } i \text{ succeeds} \\ 0 & \text{if the } k\text{th packet sent by AP } i \text{ fails} \end{cases} \tag{12}$$

If we assume the maximum MAC payload size L is used for each packet, Equation (11) can be rewritten as:

$$\begin{aligned} eTMR(i) &= \frac{L \times \sum_k \mathbb{1}\{A_i(k)\}}{\sum_k t_i(k)} \\ &= \frac{L \times P_S(i)}{T(i)} \end{aligned} \tag{13}$$

where $P_S(i)$ is the packet success probability from AP i to the joining STA given in Equation (2), $T(i)$ is the average time that AP i allocates to the joining STA for one DL packet transmission, given by:

$$T(i) = T_p(i) + T_{OH}(i) \tag{14}$$

and $T_p(i)$ is the time for AP i to transmit MAC payload to the joining STA, and $T_{OH}(i)$ is the average overhead of one packet transmission from AP i. Substituting Equation (14) into (11) and rearranging the terms, we obtain:

$$\begin{aligned} eTMR(i) &= \frac{L \times P_S(i)}{T(i)} = \frac{L \times P_S(i)}{T_p(i) + T_{OH}(i)} \\ &= \frac{L}{T_p(i)} \times P_S(i) \times \frac{T_p(i)}{T_p(i) + T_{OH}(i)} \\ &= R_{\text{MAC}}(i) \times P_S(i) \times \frac{T_p(i)}{T_p(i) + T_{OH}(i)} \end{aligned} \tag{15}$$

where $R_{\text{MAC}}(i) = L/T_p(i)$ is the MAC rate used by AP i for the joining STA to modulate MAC payload. Substituting Equation (2) into (15), we obtain the following metric for AP i:

$$eTMR(i) = R(i)\times(1-P_C(i))\times(1-P_e(i))\times\frac{T_p(i)}{T_p(i) + T_{OH}(i)} \tag{16}$$

where $P_C(i)$ is the DL collision probability given in Equation (6), and $P_e(i)$ is the DL channel error probability given in Equation (7).

The metric shown in Equation (16) is more appropriate than the conventional received signal strength based metric. Specifically, the conventional method chooses the AP with the strongest received signal strength because higher received signal strength implies higher MAC rates and smaller channel error probability. In contrast, our proposed metric not only captures the effects of received signal strength as reflected in MAC rate $R(i)$ and channel error probability $P_e(i)$, but also takes into account the interference as reflected in collision probability $P_C(i)$. In addition, this metric considers the effects of packet retransmission and overhead. Equation (16) expresses the expected true MAC layer data rate that an AP can offer to an STA, i.e., the expected number of successful MAC payload bits per channel time allocated to the STA by the AP, including packet transmission and retransmission time, backoff duration, and other overheads. Next we explain how to estimate each component in Equation (16) in order for the joining STA to optimally select the AP.

$R(i)$ depends on SNR_i from AP i to the joining STA. Assuming the function to map SNR to MAC rate is known, the MAC rate $R(i)$ used by AP i can be predicted as long as SNR is estimated as in Equation (8).

$T_p(i)$ is the time to transmit MAC payload. It depends on the payload size L in bits and MAC rate $R_{\text{MAC}}(i)$

$$T_p(i) = \frac{L}{R_{\text{MAC}}(i)} \tag{17}$$

Maximum payload is typically used in WLANs to improve transmission efficiency.

$T_{OH}(i)$ is the average overhead time including preamble, PLCP header, MAC header and CRC, all possible inter-frame spacing time, ACK time, and backoff time. The derivation is given in [21].

Once $T_{OH}(i)$ and the corresponding values in Equations (6), (7), and (17) are estimated by the joining STA, Equation (16) can be used to evaluate and compare $eTMR(i)$ for all candidate APs in order to select the "optimal" one. The proposed algorithm is summarized in Algorithm 1.

Algorithm 1 AP Selection Algorithm

The joining STA scans for APs and gets candidate AP set $\mathcal{A}$
Collect local BI for 3 seconds
Receive BI signal from all APs in $\mathcal{A}$
for each AP $i \in \mathcal{A}$ **do**
    compute $eTMR(i)$
end for
The joining STA selects AP with largest $eTMR$

IV. Performance Evaluation

We use NS-2.31 to simulate 802.11b networks in infrastructure mode. This can be easily extended to other standards, such as 802.11g or 802.11n. The NS simulator has been modified to compute collision probability as described in [19]. The transmission range of nodes is 100m, and no fading or shadowing is used in our path loss model. Each STA receives DL traffic from its serving AP. Each DL stream consists of traffic from a Constant Bit Rate (CBR) application which is generating packets at rates that saturate the network. UDP is used as the transport layer protocol. MAC retry limit is set to be 10. Both the transmit and receive antennas have 0 dB gain. We run four different scenarios for AP and STA placements:

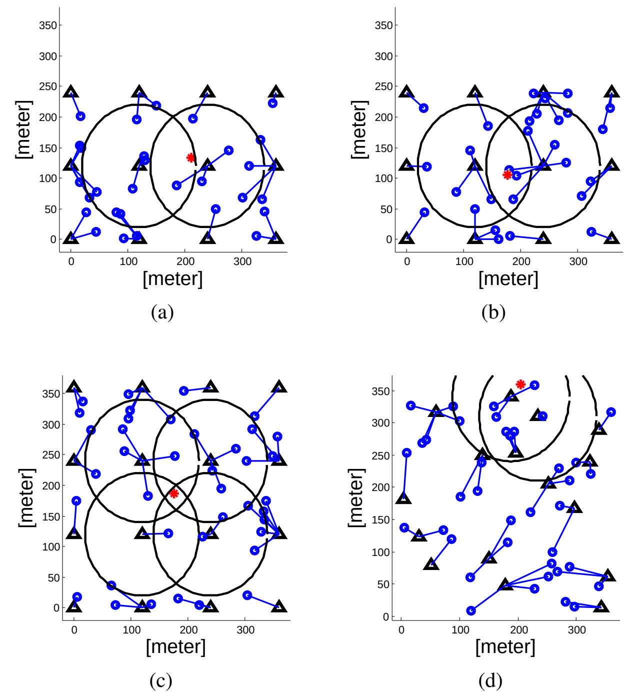

Figure 2. Example Topologies. Small Circle: STAs. Big Circle: AP's range. Triangle: APs. Star: the joining STA. A line connecting an STA to an AP: the STA is associated to the AP. (a) scenario A; (b) scenario B; (c) scenario C; (d) scenario D.

A. 12 APs are placed on a 3×4 grid with 30 STAs placed at random in space, where STAs are randomly placed by a spatial Poisson process. The joining STA can choose from two potential APs. See Figure 2(a).
B. 12 APs are placed on a 3×4 grid with 30 STAs placed at random in space, where half of the APs have significantly more STAs associated with them than the other half of the APs. The joining STA can choose from two potential APs. See Figure 2(b).
C. 16 APs are placed on a 4×4 grid with 40 STAs placed at random in space, where STAs are randomly placed by a spatial Poisson process. The joining STA can choose from four potential APs. See Figure 2(c).
D. 16 APs and 40 STAs placed at random in space. The joining STA can choose from a random number of potential APs. See Figure 2(d).

For each of the above scenarios, we run 500 to 1200 trials. To determine the ground truth, for each test trial we fix AP and STA locations and run the simulations under the exact same condition except that the joining STA associates to different APs in order to determine the highest throughput AP, which we call "optimal", by collecting the throughput from all available APs to the joining STA. Next we run the proposed AP selection

Table I. SIMULATION RESULTS: AP SELECTION STATISTICS

Scenario	Percentage of non-optimal selections			Percentage of Different Selections
	eTMR	rxpwr	Percentage Change	
A	14.7%	14.1%	5%	13%
B	14.0%	18.9%	−26%	13%
C	28.0%	83.5%	−66%	82%
D	27.5%	31.0%	−11%	15%

Table II. SIMULATION RESULTS: THROUGHPUT: (A) SCENARIO A. (B) SCENARIO B. (C) SCENARIO C. (D) SCENARIO D.

	Throughput (kbps)			Percentage Change	
	eTMR	rxpwr	optimal	eTMR vs. rxpwr	eTMR vs. optimal
For trials that decisions made by eTMR and rxpwr are different					
Average	48.76	32.38	60.13	51%	−19%
10%-tile STA	9.7	3.77	19.93	157%	−51%
Median STA	34.48	25.86	44.17	33%	−22%
90%-tile STA	110.97	67.33	126.05	65%	−12%
For all valid trials					
Average	108.04	105.98	112.74	1.9%	−4%

(a)

	Throughput (kbps)			Percentage Change	
	eTMR	rxpwr	optimal	eTMR vs. rxpwr	eTMR vs. optimal
For trials that decisions made by eTMR and rxpwr are different					
Average	53.44	31.62	73.12	69%	−27%
10%-tile STA	7.54	7	25.86	8%	−71%
Median STA	38.25	26.93	58.18	42%	−34%
90%-tile STA	106.12	59.25	138.98	79%	−24%
For all valid trials					
Average	99.12	96.34	105.04	2.9%	−6%

(b)

	Throughput (kbps)			Percentage Change	
	eTMR	rxpwr	optimal	eTMR vs. rxpwr	eTMR vs. optimal
For trials that decisions made by eTMR and rxpwr are different					
Average	24.85	6.69	28.82	271%	−14%
10%-tile STA	1.62	0	2.69	n/a	−40%
Median STA	18.31	1.08	23.7	1595%	−23%
90%-tile STA	52.79	23.7	59.25	123%	−11%
For all valid trials					
Average	25.47	10.53	30.12	142%	−15%

(c)

	Throughput (kbps)			Percentage Change	
	eTMR	rxpwr	optimal	eTMR vs. rxpwr	eTMR vs. optimal
For trials that decisions made by eTMR and rxpwr are different					
Average	586.3	190.96	721.37	207%	−19%
10%-tile STA	3.77	0	23.16	n/a	−84%
Median STA	109.96	33.4	238.09	229%	−54%
90%-tile STA	1526.2	543.51	2004.1	181%	−24%
For all valid trials					
Average	642.17	610.69	811.86	5%	−21%

(d)

algorithm ($eTMR$) described in Algorithm 1 and compare its selections with those obtained from the traditional strongest received signal strength ($rxpwr$) algorithm in which the AP with the strongest received signal strength is chosen.

A. 12 APs on Grid, 30 STAs Uniformly Placed at Random

This example topology is shown in Figure 2(a). The APs are located on a 3×4 grid where the length of each cell edge is 120m. The 30 STAs are randomly placed by a spatial Poisson process in a $240m \times 360m$ area bounded by the four outermost APs, with the constraint that the joining STA is located at the intersection of the two center APs' transmission ranges. The reason for this constraint is to ensure that the joining STA is

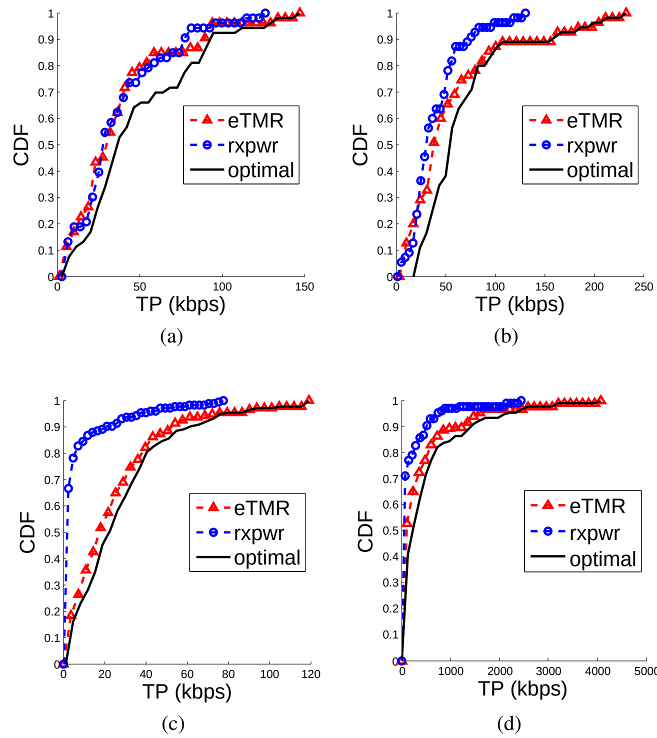

Figure 3. CDF of average throughput(TP) when selections are different: (a) scenario A; (b) scenario B; (c) scenario C; (d) scenario D.

not affected by any "corner effects", where the corner STAs do not experience any inter-BSS interference, thus violating our assumptions.

In this scenario, 1000 trials were run, and 220 trials were discarded since their optimal throughput was less than 1kbps and the joining STA was not in the overlapping region of two APs. We call these discarded trials "invalid". The decision statistics of AP selection algorithms are summarized in Table I. The percentage of non-optimal selections made by $eTMR$ and $rxpwr$ for this scenario are both close to 14%. The two AP selection algorithms made different decisions in 13% of the valid trials. The CDF of throughput for cases in which the decisions are different is shown in Figure 3(a). Some of the key throughput statistics of the CDF are summarized in Table II(a). Even though the percentage of non-optimal selections made by the two AP selection algorithms is similar, the $eTMR$ algorithm on average results in 51% higher throughput than $rxpwr$ in situations when selections made by the two algorithms are different. It is also interesting to note that the average throughput over all valid simulation trials obtained by $eTMR$ algorithm is within 4% of the throughput in optimal AP selection. However, comparing $eTMR$ to $rxpwr$, the average throughput over all valid simulation trials rather than the trials in which the decisions are different, is only improved by 1.9%; this is mainly due to the fact that the percentage of different selections made by the two algorithms is small, and the inter BSSs hidden node interference for DL transmissions in this scenario is not high.

B. 12 APs on Grid, 30 STAs Non-Uniformly Placed at Random

This scenario is to simulate the situations where the number of STAs associated with available APs are dramatically different. One example topology is shown in Figure 2(b). The location of the APs is the same as that in Figure 2(a). The 30 STAs are randomly distributed in a $240m \times 360m$ area bounded by the four outermost APs, and the ratio of the number of STAs located in the left and the right half plane is roughly $1:2$. The joining STA is located at the intersection of the two center APs' transmission ranges.

In this scenario, 1000 trials were run, and 237 invalid trials were discarded since the optimal throughput was less than 1kbps and the joining STA was not in the overlapping region of two APs. The decision statistics of AP selection algorithms are summarized in Table I. The percentage of non-optimal selections by $eTMR$ is 26% lower than that of $rxpwr$. Similar to scenario A, the percentage of different decisions made by the two algorithms is small, i.e., only about 13% of the valid trials. The CDF of throughput for cases in which the decisions are different is shown in Figure 3(b), and some key statistics are summarized in Table II(b). As in the previous scenario, $eTMR$ achieves higher throughput than $rxpwr$, which can be observed in Figure 3(b) as the CDF curve obtained from $eTMR$ is closer to the optimal curve than the $rxpwr$ curve. The average throughput improvement for $eTMR$ over $rxpwr$ is 69% when selections differ. $eTMR$ only improves average throughput over all valid simulation by 2.9% as compared to $rxpwr$, mainly due to the fact that the percentage of different selections made by the two algorithms is small and the inter BSSs hidden node interference for DL transmissions in this scenario is not high. Similar to scenario A, the average throughput over all valid simulation trials obtained by $eTMR$ is within 6% of the throughput achieved by optimal AP selection.

C. 16 APs on Grid, 40 STAs Uniformly Placed at Random

We now examine the performance when the joining STA can select from more than two APs. One example topology is shown in Figure 2(c), which consists of 16 APs and 40 STAs. The APs are located on a 4×4 grid where the length of the grid is $120m$. The 40 STAs are randomly placed by a spatial Poisson process in a $360m \times 360m$ area bounded by the four outermost APs, with the constraint that the joining STA is located at the intersection of the four center APs' transmission ranges.

In this scenario, 500 trials were run, and 264 invalid trials were discarded since the optimal throughput was less than 1kbps and the joining STA was not in the overlapping region of two APs. The decision statistics of AP selection algorithms are summarized in Table I. Noticeably, the percentage of different decisions made by the two algorithms is about 82% of all the valid trials, and the proposed $eTMR$ algorithm reduces the percentage of non-optimal selections by 66%. The reason is that in this scenario there are more APs to choose from and the inter BSSs hidden node interference at APs' intersection region is more severe as compared to previous scenarios. The $rxpwr$ algorithm performs worse when the interference becomes a more significant factor in a network. Figure 3(c) plots the CDF of throughput for cases when selections are different, and Table II(c) summarizes some of the key statistics. The average throughput improvement for $eTMR$ over $rxpwr$ is 271% when selections differ. $eTMR$ improves the average throughput over all valid trials by 142% as compared to $rxpwr$. This scenario is particularly interesting since with more APs to choose from, there is potentially more inter-BSS hidden node interference and our proposed algorithm shows greater benefits. However, it is important to recognize that the area with four overlapping APs is quite small, i.e., 6% of the test area.

D. 16 APs 40 STAs Randomly Placed

In the last scenario both APs and STAs are randomly placed mimicking typical hyper dense scenarios observed in practice. One example topology is shown in Figure 2(d), where the simulation area is $360m \times 360m$. To reduce simulation overhead, we pre-generate three different sets of random locations for the 40 APs with the following constraints: 1) the APs cover the entire simulation area, 2) the APs have 20 meter minimum separation distance. Each trial in this scenario places all 16 APs based on one of the three sets of random AP locations. The 40 STAs are placed at random according to a spatial Poisson process. Note there is no constrain on the placement of the joining STA's location. The overlapping region of at least two APs' transmission ranges is 89% of the total area. This implies that if a STA arrives randomly in these random topologies, it needs to select from greater than or equal to two APs with an 89% probability.

In this scenario, 1200 trials were run, and 89 invalid trials were discarded since the optimal throughput was less than 1kbps. The decision statistics of AP selection algorithms are summarized in Table I. The proposed $eTMR$ algorithm reduces the percentage of non-optimal selections by 11% as compared to $rxpwr$, and the two algorithms made different decisions in 15% of all valid trials. The CDF of throughput for cases when selections are different is plotted in Figure 3(d) and some key statistics are summarized in Table II(d). The average throughput gain for $eTMR$ over $rxpwr$ is 207% when selections differ, and 5% for all valid trials.

Figure 4(a) plots the count of the number of APs for the joining STA to choose from for all valid trials. In 115 out of 1200 trials the joining STA can only hear one AP, which is 10.3% of the total trials. This is consistent with the topology

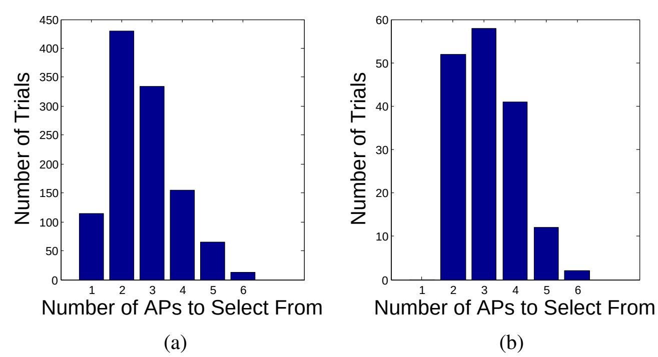

Figure 4. Count of the number of APs to select from for scenario D for: (a) all valid trials; (b) trials with different decisions

Table III. SIMULATION RESULTS: SCENARIO D

	Number of APs to Select From		
	2	3	4
% different selection conditioned on # of APs	12%	17%	27%
eTMR reduction in non-optimal selection	3%	5%	42%
For trials that decisions made by eTMR and rxpwr are different			
eTMR average TP (kbps)	351.42	387.4	669.59
rxpwr average TP (kbps)	196.05	210.81	135.02
Gain for eTMR over rxpwr	79%	84%	396%
For all valid trials			
eTMR average TP (kbps)	716.05	614.28	724.96
rxpwr average TP (kbps)	697.23	564.45	582.64
Gain for eTMR over rxpwr	3%	9%	24%

generation where a STA can hear more than one AP in 89% of the simulation area. Figure 4(b) shows the same plot but for the case when $eTMR$ and $rxpwr$ select differently. Generally speaking, as the number of APs to choose from increases, so does the number of cases in which $eTMR$ makes a different decision than $rxpwr$. Table III summarizes the throughput data and selection statistics for different number of APs for the joining STA to select from. When the joining STA can hear from two APs, the percentage of different selections is 12%, which is close to the results in scenario A as in Table I. However, when the joining STA can choose from four APs, the percentage of different selections is 27%, which is significantly smaller than scenario C. This is because in random topology the APs may be able to hear each other, while in scenario C the four APs are guaranteed to be out of each other's transmission range. This observation implies that an AP within range of another AP does not cause any inter BSSs interference, and consequently the APs share the same channel over time. When multiple APs can hear each other, the APs have to wait while another AP is active, and hence the spatial frequency reuse of WLAN decreases. As a result, the overall network throughput decreases, and the DL throughput that each AP can offer is also reduced. From the lower half of Table III, we conclude that in general, the average throughput gain increases with the number of available APs to choose from for both valid trials and for trials with different selections.

V. CONCLUSION

In this paper we proposed a new AP selection algorithm which considers the inter-BSS interference and collisions, by exploiting BI signals both at the AP and at the joining STA. The proposed scheme achieves as much as 207% throughput gain when selections are different in random scenarios as compared to the traditional received signal strength based method. For all valid simulation trials the gain is 5%.

Future work includes extending the current work to AP selection for UL traffic, studying the impacts of our AP selection algorithm on aggregate network throughput, and extending current static algorithm to dynamic AP selection in which STAs can switch to different APs.

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