A Multi-AP Architecture for High-Density WLANs: Protocol Design and Experimental Evaluation

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Abstract—Fast proliferation of IEEE 802.11 wireless devices has led to the emergence of High-Density (HD) Wireless Local Area Networks (WLANs), where it is challenging to improve the throughput because each device has to share channel with all the other devices within its carrier sensing range. Although the existing adaptive Physical Carrier Sensing (PCS) techniques can improve the throughput, they result in high frame loss rate. In this paper, we investigate a Multi-AP (MAP) architecture, in which each user can associate with multiple APs according to the network topology and traffic distribution, for adaptive PCS based HD-WLANs. One of important features of the MAP architecture is that it can obtain Multi-AP diversity in both uplink and downlink. In uplink (from users to APs) the frame loss rate can be decreased by combining the reception of all associated APs, and in downlink the throughput can be improved significantly by dynamically selecting one of associated APs for transmissions according to the channel fading and traffic distribution. We first study the uplink and downlink performance of the MAP theoretically, and then propose an AP association algorithm for deciding which APs to associate with, an AP selection algorithm for dynamically selecting an AP for downlink transmissions, and an ACK management solution for avoiding ACK collisions. We build a testbed based on Intel StarEast platform to make real experiments for performance evaluation. In a typical experiment scenario, compared to the scheme with the adaptive PCS only, up to 30% throughput gain can be observed in uplink, and nearly 100% throughput gain can be found in downlink.

I. INTRODUCTION

The past few years have seen a tremendous growth in the deployment of Wireless Local Area Networks (WLANs) conforming to the IEEE 802.11 standard [3]. In [2], the authors showed that large-scale WLANs with HD deployment of users and Access Points (APs) have emerged widely in various hotspots.

From [4], in WLANs the signal-to-interference-and-noise ratio (SINR) required for successfully decoding increases with the data rate quickly from 13.962 dB (6 Mbps) to 63.807 dB (54 Mbps). Correspondingly, the ratio of the interfering radius to the transmitting radius is generally larger than 4. However, the number of available channels in WLANs is limited (e.g., just 3 non-overlaying channels in IEEE 802.11b/g, and 12 in IEEE 802.11a), and thus WLANs cannot scale the network only by frequency multiplexing. Alternatively, WLANs employ spatial reuse [14] to make the network capacity scalable, i.e., many neighboring APs work in the same channel and use Physical Carrier Sensing (PCS) to alleviate interferences. WLANs are Carrier Sensing Multiple Access (CSMA) based. Before transmitting, each user senses the channel signal strength. If it is beyond a threshold called PCS threshold, the user suspends the transmission till it falls below the PCS threshold. Thus, CSMA enforces each user to content channel with all users in its PCS range. In HD-WLANs, the throughput of each user is depressed seriously due to too many users within its PCS range. To address this issue, in [5] we proposed some adaptive PCS algorithms to tune the PCS threshold according to the link and network conditions. The core idea of these algorithms is to shrink the PCS range so as to enhance the spatial reuse efficiency. However, the adaptive PCS algorithm increases the frame loss rate, defined as the ratio of colliding transmissions to total transmissions, due to hidden terminals. Extensive analytical and simulation results show that the frame loss due to hidden terminals reach (nearly 30 – 50%) when the throughput approaches to the maximum. Therefore, it is challenging to decrease the frame loss rate in HD-WLANs with adaptive PCS.

In [2], the authors indicated that in current most hotspots each user can find multiple APs (3 - 20) within its reception range. Because APs are becoming cheaper and cheaper (just 10 dollars or less), the density of APs is increasing quickly. Different from traditional WLANs, where each user associates with one AP only, in [18] we proposed a concept of Multi-AP (MAP), where each user is capable of associating with multiple APs within its reception range. Then, an uplink data transmission is successful as long as one of the associated APs receives the data frame. For the uplink transmission of a user, different APs have different hidden terminals, and thus the frame losses of different APs are not correlated completely. Therefore, such a MAP architecture is a promising solution to achieve AP diversity in uplink for HD-WLANs with adaptive PCS.

In this work, we focus on the adaptive PCS based HD-WLANs, where each device can tune the PCS threshold with the algorithm proposed in [5]. The purpose of this paper is to design a series of MAP-efficient MAC protocols for practical deployment, which include an AP association algorithm, a downlink AP selection algorithm for dynamically selecting one AP for downlink transmissions, and an ACK management solution used for avoiding ACK collisions.
collisions. We first analyze the behaviors of users in both uplink and downlink, and point out the factors influencing the throughput performance. Then, based on the analytical results, we propose the detailed algorithms for practical deployment of MAP. To validate the proposed algorithms, a StarEast platform, which has full functionalities of laptop but cheaper, is employed for practical deployment. With the support of open source drivers and firmware, the proposed algorithms and the PCS algorithm proposed in [5] are implemented. The experimental results show that the AP association algorithm successfully selects the AP set with similar performance of associating with all APs in the reception range, but with less overhead. In downlink, the AP selection algorithm can balance the traffic load among neighboring APs and achieve significant gain compared to that of Single AP. Moreover, the experiment shows that the ACK management scheme works well under the support of current wired links.

The rest of this paper is organized as follows. Related work on our topic is summarized in Section II. In Section III, we give a simple description to the MAP architecture. Then, Section IV is devoted to the analysis on the rules influencing the uplink and downlink performance. In Section V, an AP association algorithm and an AP selection algorithm are proposed according to the analytical results in Section III. An ACK management solution is given in Section VI. Extensive experimental results are given in Section VII. Finally, the conclusions are drawn in Section VIII.

II. RELATED WORK

With increasing development of network scale, much attention has been attracted to the schemes for HD-WLANs. Early work concentrates on exploiting the variation of wireless fading channel to increase the one-hop transmission rate, and the typical schemes can be found in [7][11][12]. In recent several years, more and more work [13][16] focuses on how to allow more simultaneous transmissions by means of spatial reuse techniques. The key principle of spatial reuse is to adjust the PCS range in terms of the distance of transmitter-receiver to shrink the cell size. With the capture effect, more users can survive interference and transmit concurrently. Extensive work have shown that an aggressive adaptive PCS threshold, which allows the existence of hidden terminals, can enhance the throughput significantly. However, the aggressive adaptive PCS brings higher frame loss rate due to hidden terminals, which can be alleviated with the MAP architecture proposed in this paper. In [5], we extend existing PCS tuning algorithms and proposed a heuristic algorithm to achieve the optimal PCS threshold in practical networks. In this paper, all devices employ the PCS tuning algorithm proposed in [5] directly.

With respect to architecture level schemes proposed to improve the throughput, the schemes of “Thin-AP” [19][20], MultiNet [21][23] and MRDC [6] are the most relevant to our work. “Thin-AP” is an important industry solution to solve the seamless handoff in HD-WLANs. In “Thin-AP” solution, the management function of APs is moved to an Access Controller (AC), which is responsible for the association, i.e., users associate with the AC instead of APs. Then, by configuring all APs with the same MAC address and BSSID, from the viewpoint of users, all APs are treated as one AP controlled by the AC, it is not necessary to re-associate when roaming. However, the “Thin-AP” solution cannot enable multiple APs to serve one user simultaneously, and thus it cannot alleviate the hidden terminal problem caused by adaptive PCS. In [21][23], Chandra et.al. proposed a software-based approach, called MultiNet, that facilitates simultaneous connections to multiple networks by virtualizing a single wireless card. MultiNet is capable of providing multiple associations for each user. However, MultiNet is a network layer solution, and it does not exploit the open feature of wireless environment. Therefore, MultiNet cannot obtain the diversity gain of multiple associations. A similar network solution can be found in [24] and the references therein. In [6], the authors proposed a frame combining technique, which based on a Multi-AP architecture, to improve the frame loss due to channel fading. Due to no consideration on collisions and spatial reuse, the authors thereby did not further investigate the potential advantages in alleviating the hidden terminal problem from network perspective, and the performance in downlink was not considered. Our work filled up this vacancy, and systematically investigated its performance and deployed a practical MAP network.

The method of AP selection is not specially stated in the standard [3], and in most practical IEEE 802.11 products the user tends to select the AP with the strongest signal strength. In literature, the authors in [8][9][10] investigated the problem of AP selection with the assumption that different APs work in different channels. They pointed out that ignoring the effect of the load distribution will lead to inefficient use of the bandwidth. Under their assumptions, the user can freely associate with any AP in its transmission range without considering the resulted interference to other APs because that different APs work in different channels. However, in the considered HD-WLANs with a single channel, the interference to other APs, which directly influences the spatial reuse efficiency, should be considered. To the best of our knowledge, the research on AP selection considering load distribution in the considered scenario is still void.

III. MAP ARCHITECTURE

In WLANs, users and APs working in different orthogonal channels cannot communicate with each other, and thus as shown in Fig.1 the whole network can be divided into several physically independent sub-networks by orthogonal channels. With some carefully designed channel assignment algorithms, in HD-WLANs the network traffic load can be balanced in some degree at the stage of network deployment. As indicated in [2], the number of APs within the reception range is much larger than the number of orthogonal channels, and thus after the channel assignment each user can easily find multiple APs working in the same channel within its reception range. The MAP architecture is based on a sub-network in which

1Herein, Single AP refers to that each user associates with one AP only.
all users and APs work in the same channel, and then the whole network can be divided into multiple MAP sub-networks. The MAP architecture is logically independent of the channel assignment. Therefore, all schemes developed in the MAP architecture can be jointly implemented with existing channel assignment schemes.

In addition, the MAP solution is a MAC-solution, and all existing high-layer (TCP/IP, application layer) protocols and services can be implemented upon the MAP without any modifications. Therefore, only MAC-layer devices are depicted in this paper.

A. A simple description to MAP architecture

A typical MAP architecture is shown in Fig. 2. Similar to the “Thin-AP” architecture, three types of devices are involved in the MAP architecture: AC, AP and user.

The AC manages the APs with the IETF CAPWAP protocol [1], and is responsible for building and maintaining an association list. All algorithms developed in this paper are implemented in the AC, and thus the MAP brings few modifications to existing WLANs. Each AP has two suits of physical interfaces: one is wireless radio interface for communicating with users, the other one is wired interface for the connection with the AC. In the MAP, all APs managed by the same AC are configured with the same MAC address and BSSID, and they move the association function to the AC by directly forwarding association requests to the AC. At the association stage, all APs within the considered user’s reception range will forward the association request to the AC, and then the AC selects some of them to build an association list for the considered user according to the network condition of each AP. After that the AC informs the association results to the corresponding APs.

In downlink, the AC can dynamically select one of the associated APs, according to the channel strength and the traffic load, to transmit data packets to the considered user. Therefore, the MAP can achieve multi-AP diversity in downlink as well.

B. Open Issues

However, it is challenging to deploy a practical MAP network because there are some open issues:

1) AP association: the multi-AP diversity gain depends on the associated AP set. Generally speaking, the gain increases with the number of APs associated. However, too many APs will involve considerable overhead due to information exchange in association and ACK management. Therefore, an AP association scheme is required to decide the AP set for association.

2) AP selection in downlink: in general, the MAP network has high-density deployment, where the traffic load distribution is more complicated than sparse networks. To balance the traffic load among neighboring APs, a flexible AP selection in downlink, which can enable the AC positively select the AP with less traffic load for transmissions, is required.

3) ACK management: the main purpose of ACK management is to avoid ACK collisions. With traditional “stop-and-wait” ACK mechanism, an intuitive solution is that: after receiving a data frame the associated AP creates an ACK request frame including the sequence ID of the data frame and forwards it to the AC, and the AC select only one of the APs that decode the same data frame to return the ACK with a certain rule (first come first serve or minimum traffic load). From the standard, in order not to influence the backoff mechanism of the user, the whole time of ACK management must be smaller than a SIFS (the interval between the data frame and the ACK frame, just several microseconds). However, experimental results show that the cost in ACK management described above is more than 10 milliseconds. Thus, an ACK management solution should be proposed.

IV. THEORETICAL ANALYSIS FOR MAP

To fully exploit the features of the MAP architecture, an analytical model is proposed to investigate the behaviors of users and APs in downlink and uplink.
A. System model

Considering a MAP network with \( M \) APs and \( N \) users, we index each AP with \( A_i \) (\( i = 1, 2, ..., M \)) and user with \( U_j \) (\( j = 1, 2, ..., N \)). All APs and users are deployed over the 2-D plane. The transmissions occur between users and APs only. To clarify the presentation, the transmissions from users to APs are called uplink transmissions, and the reverse transmissions are called downlink transmissions.

The transmit powers of \( A_i \) and \( U_j \) are denoted by \( P_{t,A_i} \) and \( P_{t,U_j} \), respectively. The distance between \( A_i \) and \( U_j \) is denoted by \( d_{i,j} \), and the corresponding channel gain is denoted by \( g(d_{i,j}) \) which is a function with respect to \( d_{i,j} \).

With the typical pathloss model \([25]\), \( g(d_{i,j}) \) is given by

\[
g(d_{i,j}) = g_0 d_{i,j}^{-\alpha} \tag{1}\]

where \( g_0 \) is a constant, and \( \alpha \) is the path loss coefficient, ranging from 2 (free space) to 4 (indoor).

In the MAP architecture, each user is allowed to associate with multiple APs. Let \( \Theta_j \) denote the set\(^2\) of APs those associate with \( U_j \). For the uplink originated by \( U_j \) a transmission is successful as long as any one in \( \Theta_j \) decodes the packet transmitted. For the downlink, the AC selects one AP among \( \Theta_j \) for transmissions according to the channel fading and traffic distribution. In addition, let \( \Phi_i \) denote the set of the users associated to \( A_i \).

Let \( \gamma \) denote the required signal-to-interference-noise ratio (SINR) for decoding, which varies with the data rate. Then, the condition that \( A_i \) receives the frame of \( U_j \) successfully is that during the transmission

\[
P_{t,A_i} g(d_{i,j}) \geq \gamma; \tag{2}\]

holds, where \( N_0 \) is the power of thermal noise and \( P_t \) is the interference from neighboring transmissions. Let \( E_{i,j} \) denote the event that \( A_i \) receives the frame of \( U_j \) successfully, then the probability that \( E_{i,j} \) occurs is given by

\[
P(E_{i,j}) = P\left(P_t \leq \frac{P_{t,A_i} g(d_{i,j})}{\gamma} - N_0\right) \tag{3}\]

The reason of \( P_t > \frac{P_{t,A_i} g(d_{i,j})}{\gamma} - N_0 \) is that there are some hidden terminals start concurrent transmissions\(^3\). In Fig.3, the PCS range and the interfering range are described by solid line and dash line, respectively. Then, for link from \( U_1 \) to \( A_1 \), \( U_4 \) is a hidden terminal, and similarly, \( U_5 \) is the hidden terminal of link from \( U_1 \) to \( A_2 \). Let \( p_{A_1} \) and \( p_{U_j} \) denote the probabilities that \( A_1 \) and \( U_j \) working in transmitting state, respectively. Then, from Fig.3, the probabilities that \( A_1 \) and \( A_2 \) receive the frames of \( U_1 \) successfully is respectively given by

\[
\begin{align*}
P(E_{1,1}) &= 1 - p_{U_4} \\
P(E_{2,1}) &= 1 - p_{U_5} \tag{4}\end{align*}
\]

\(^2\)In traditional WLANs, there is only one item in \( \Theta_j \).

\(^3\)The probability that a collision occurs due to simultaneous transmissions is much smaller than that due to concurrent transmissions of hidden terminals, and thus it is assumed that the collision is caused by hidden terminals only.

If \( U_1 \) associates both \( A_1 \) and \( A_2 \), the frame loss rate (\( P_L \)) is given by

\[
P_L = pu_4pu_5 \tag{5}\]

which is smaller than that of associating only one AP (\( A_1 \) or \( A_2 \)). This is one of important contributions of MAP.

In the remainder of this section, we will investigate the detailed features of MAP in both uplink and downlink.

B. Uplink

Let \( S \) denote the average throughput per user, defined as the average payload transmitted by a user terminal in a time slot. In a HD-WLAN, \( S \) is given by

\[
S = \frac{C(1 - P_L)}{n_c} \tag{6}\]

where \( C \) is the one-link capacity, and \( n_c \) is the number of transmitters within the PCS range (include the user itself). Herein, \( C \) is in proportion to the physical data rate, and is independent of the PCS range.

To maximize the throughput of each user, the adaptive PCS proposed in [5] is employed, which can achieve

\[
\max S = \frac{C(1 - P_L)}{n_c} \tag{7}\]

by tuning the PCS threshold in distributed mode.

Although the adaptive PCS can achieve high throughput, it results in high frame loss rate\(^4\). In a MAP network the user associates with multiple APs, and then the corresponding frame loss rate is given by

\[
P_L = 1 - P\left(\bigcup_{i \in \Theta_j} E_{i,j}\right) \tag{8}\]

With the help of Fig.3, we can understand the performance improvement provided by MAP intuitively. The frame loss rate of the user with multiple associations is always not higher than that with single association. The performance gain depends on the relativity among \( \{E_{i,j} | \theta_j \in \Theta_i\} \). In Fig.3, \( U_4 \) and \( U_5 \), which are respectively the hidden terminals of \( A_1 \) and \( A_2 \), cannot sense each other, and thus \( E_{1,1} \) and \( E_{2,1} \) is considered to be independent. Correspondingly, the frame loss rate is given by \( pu_4pu_5 \), which is smaller

\(^4\)From the viewpoint of TCP layer, high frame loss rate will lead to more TCP retransmissions, which decreases the transmission window frequently and depresses the TCP throughput.
than $p_{U_i}$ and $p_{U_j}$. Differently, if the hidden terminals of $A_1$ and $A_2$ are the same, associating both $A_1$ and $A_2$ cannot improve the frame loss rate.

By substituting (8) into (7), a joint throughput optimization can be considered. However, from (8), we find that $P_L$ depends on the AP topology and practical AP association algorithm. A theoretical joint optimization is too complicated to be achieved, and thus it is out of the scope of this paper. As the analysis above, the performance improvement brought by MAP depends on the topology, and associating multiple APs brings the cost in information exchange for association and ACK management. Therefore, an AP association algorithm will be required.

**C. Downlink**

In downlink, the users in a MAP network can obtain Multi-AP diversity as well by selecting one associated AP with minimum traffic load for downlink transmissions. From the CSMA mechanism, each AP shares channel with all devices within its PCS range. Let $\mu(A_i)$ denote the traffic load within the carrier sensing range of $A_i$. We take Fig.3 for example, where $\{A_2, U_1, U_2\}$ fall in the carrier sensing range of $A_1$ and $\{A_1, U_1, U_2, U_3, U_5\}$ fall in the carrier sensing range of $A_2$. Then, we have

$$\begin{align*}
\mu(A_1) &= p_{A_1} + p_{U_1} + p_{U_2}, \\
\mu(A_2) &= p_{A_1} + p_{U_1} + p_{U_2} + p_{U_3} + p_{U_5}.
\end{align*}$$

(9)

Let $f_{i,j}$ denote the traffic load from $A_i$ to $U_j$, and herein $j \in \Psi_i$ where $\Psi_i$ denotes the user set employing $A_i$ as downlink AP. From the standard, the arrival data frame served with first-in-first-out (FIFO) mode, and thus the maximum time assigned for $U_j$ is given by $\sum_{k \in \Theta_i} f_{i,k} (1 - \mu(A_i))$. It is well known that the slot time for backoff is much smaller than the transmission time, and thus the IEEE 802.11 MAC mechanism can be approximated by a $p$-persistent slotted-ALOHA. Correspondingly, the access delay which is defined as the time from the point that the data frame becomes the queue head at the AP to the point that the data frame is received successfully by the related user, is considered to be exponentially distributed. If the arrival process is assumed to be a Markov process. The delay, which is the sum of queueing delay and access delay, is given by

$$d_{i,j} = \frac{(1 - P_{L_{i,j}}) \sum_{k \in \Psi_i} f_{i,k} (1 - \mu(A_i))}{(1 - P_{L_{i,j}}) \sum_{k \in \Psi_i} f_{i,k} (1 - \mu(A_i)) - f_{i,j}}$$

(10)

where $P_{L_{i,j}}$ denote the frame loss rate of link from $A_i$ to $U_j$. From (10), it is observed that minimizing the delay is equal to selecting the AP with maximum $\frac{1 - P_{L_{i,j}}}{\sum_{k \in \Psi_i} f_{i,k} (1 - \mu(A_i))}$. 

**V. AP ASSOCIATION AND AP SELECTION**

According to the analysis above, we propose an AP association algorithm and an AP selection algorithm in this section. The AP association algorithm is employed to decide which APs will be associated, and the target is to minimize the frame loss rate in uplink. The AP selection algorithm is used to select an AP among the associated AP set for downlink transmissions, and the principle is balancing the traffic load among neighboring APs and achieve the maximum throughput per user in downlink.

**A. AP association**

The AP association is divided into two stages, and the detailed description is shown as follows:

1) **Probe stage** in this stage, the user that want to associate sends several probe frames with incremental sequence. All APs within the reception range will receive the probe frames and forward the frame sequence of those successfully received to the AC.

2) **Selection stage** after the probe stage, the AC has obtained the reception status of all APs within the reception range of the considered user. Then, the AC executes a selection algorithm to decide the association set, and informs the association result to APs. The detailed selection algorithm is described in the remainder of this section.

After the probe stage, the AC creates a matrix $R = \{r_{i,j}\}_{A \times B}$ to describe the reception status, where $A$ is the number APs within the reception range and $B$ is the number of probe frames. Herein, $r_{i,j}$ indicates the reception status of the $j$th probe frame in the $i$th AP, and $r_{i,j} = 1$ means successful and $r_{i,j} = 0$ means failing. Then, the vector $R_i = [r_{i,1}, r_{i,2}, ..., r_{i,B}]$ indicates the reception status of the $i$th AP. Correspondingly, the frame loss rate of the $i$th AP is given by

$$P_L_i = 1 - \frac{\sum_{j=1}^{B} r_{i,j}}{B}$$

(11)

From (8), if the user associates multiple APs, the frame loss rate is given by

$$P_L = 1 - \frac{\sum_{j=1}^{B} \left( \bigcup_{i \in \Theta_j} r_{i,j} \right)}{B}$$

(12)

where

$$\bigcup_{i \in \Theta_j} r_{i,j} = \begin{cases} 0, & \text{all } r_{i,j} = 0, \\ 1, & \text{else}. \end{cases}$$

An intuitive conclusion from (12) is that associating all APs within the reception range results in the minimum $P_L$. However, it is well known that the more APs associated, the more overhead involved in the information exchange in association and ACK management. Therefore, the basic principle of associating APs is to associate the AP that the brought Multi-AP diversity gain is beyond a threshold. Let $\kappa$ denote the threshold, and then the associated AP $\Theta_j$ set
should have the following features:

\[
\begin{cases}
   P \left( \bigcup_{i \in \Theta_j} E_{i,j} \right) - P \left( \bigcup_{i \in \Theta_j, j \neq k} E_{i,j} \right) > \kappa, \\
   \text{for any } k \in \Theta_j
\end{cases}
\]

\[
\begin{cases}
   P \left( \bigcup_{i \in (\Theta_j \cup k)} E_{i,j} \right) - P \left( \bigcup_{i \in \Theta_j} E_{i,j} \right) \leq \kappa, \\
   \text{for any } k \in \Theta_j
\end{cases}
\]

where \( \Theta_j \) is the set of all APs within the reception range except those belong to \( \Theta_j \). It is a typical NP hard problem to select an AP set conforming to (13) with minimum frame loss rate, and the complexity of global searching is \( 2^A \). For a high-density WLAN, \( A \) is usually larger than 10 [2]. Thus, a suboptimal solution with less computational complexity should be considered.

The final target of Multi-AP association is to make the frame loss rate as small as possible. Following this target, we propose an association algorithm, which is called Minimum Frame loss rate (MF) algorithm. The pseudo code of the proposed algorithm is shown as below:

**MF AP association**

1. Obtain matrix \( R = \{r_{ij}\}_{A \times B} \) from the statistics
2. Add the AP with maximum \( \sum_{j=1}^{B} r_{ij} \) into \( \Theta_j \)
3. Do
4. Calculate \( f(k) = \sum_{j=1}^{B} (U_{i,j} \cup \Theta_j) r_{ij} \)
   
   \[ \text{for each } k \in \Theta_j \]
5. If \( \max_{k \in \Theta_j} f(k) - \sum_{j=1}^{B} (U_{i,j} \cup \Theta_j) r_{ij} > \kappa \)
6. Add the AP with maximum \( f(k) \) into \( \Theta_j \)
7. Else
8. Break, return \( \Theta_j \)
9. End do
10. Inform \( \Theta_j \) to the selected APs

Intuitively, the proposed algorithm adds the AP that can minimize the total frame loss rate to \( \Theta_j \) in each step. The final AP set \( \Theta_j \) depends on the selection of \( \kappa \) seriously. In particular, all APs within the reception range will be included into \( \Theta_j \) when \( \kappa = 0 \). The selection of \( \kappa \) mainly depends on the link condition among APs and the AC, because most of overhead comes from the ACK management among APs and the AC. Tuning \( \kappa \) achieves a tradeoff between the overhead and throughput improvement. Due to the limited space, the selection algorithm for \( \kappa \) is out of the scope of this paper. According to the experimental environment of our testbed, we set \( \kappa = 0.05 \) in our experiments.

**B. AP selection in downlink**

It is well known that the throughput is reversely in proportion to the delay, and thus the algorithm selecting the AP with maximum \( \sum_{k \in \Theta_j, j \neq k} (1 - \mu(A_i)) \) for downlink is also the method of maximizing the throughput. In practical deployment, an on-line dynamic AP selection algorithm is employed. The detailed selection algorithm for \( U_j \) is divided into two stages and described as follows:

1) **Environment measurement** in this stage, all associated APs transmit data frames to the user in round-robin mode, and then the value of \( \{ P_{i,j}, \mu(A_i), f_{i,j} \} \).

2) **Downlink AP selection** in this stage, the AP with maximum \( \sum_{k \in \Theta_j, j \neq k} (1 - \mu(A_i)) \) is selected for downlink transmission, and then the address of the selected AP is recorded in the AC. From then on, the AC forwards all data frames for \( U_j \) to the selected AP directly.

To track the variation of the network condition, the algorithm described above is executed periodically.

**VI. ACK MANAGEMENT SOLUTION**

As mentioned above, an ACK management is really a crucial point in MAP, which is employed in uplink to avoid ACK collisions. As indicated above, the traditional “stop-and-wait” mechanism is only feasible in theory, but the experimental measurement shows that with current wired link condition it costs in the order of millisecond.

To address this issue, we implement a selective NACK mechanism, which is a layer 2.5 solution. The flow chat of the proposed NACK mechanism is shown in Fig.4. The core idea is to insert a buffer between MAC layer and routing layer in both users and ACs, and it is transparent for APs. NACK is a selective retransmission mechanism. All data frames are transmitted with incremental sequence number in the format of broadcast, which disables the retransmission functionality. APs forward the data frames to the AC directly. In the added layer 2.5, the AC buffers the received frames and checks the sequence number. The duplicated frames will be dropped directly, and the sequence number of lost frames will be informed to the user by sending a frame in the format of data frame. Then, the user will retransmit the related frames buffered in its layer 2.5.

Herein, we take Fig.4 as example to show the detailed working flow of the NACK mechanism. In the figure, “Buffer 1” and “Buffer 2” show the buffer status of layer 2.5 and MAC layer of the user, respectively. At the beginning, both buffers store 4 frames. For each transmission, MAC buffer removes the transmitted frame directly due to no MAC retransmissions, but the related frame is not removed from layer 2.5 buffer. In the figure, frame 2 fails to be received, but frame 3 is received successfully. Then, the AC knows that frame 2 fails, a NACK frame, which also includes a piggyback the reception status of frame 3, is returned to the user in the format of data frame. After receiving the NACK frame, the layer 2.5 will delete the frames received successfully (frame 1 and frame 3), and copy the lost frame (frame 2) to MAC buffer for retransmissions. The retransmission frame has higher priority than normal frames, and is inserted into the queuing head of the buffer. In particular, when no failed data frames are founded in a given time (10 ms in practical implementation), a timeout counter will trigger an ACK return for informing the user the reception status. In this way, the layer 2.5 buffer of the receiver can delete the data frames received successfully in time. It is worth noting that
For the Evaluation of Uplink Frame 3

We first show the AP association. The realistic experiment show that the NACK works well in the MAP information exchange between APs and the AC. The practical measurement show that the NACK does not influence the performance of TCP/UDP. The reason is that a reorder technology is employed in Layer 3 (IP layer), which is originally for multi-path routes. The proposed NACK does not require high-speed information exchange between APs and the AC. The practical measurement show that the NACK works well in the MAP network.

VII. EXPERIMENTAL EVALUATION

The overall architecture of MAP testbed consists of APs and users remotely managed by a console, which behaves as the AC, for running experiments. Both APs and users are behaved by StarEast nodes, which are equipped with Intel 2200/2915 wireless card and an external antenna with Snapgear Linux patched to run for Intel Xscale IXP425 platform. The operation system is open source Redhat Enterprise Linux, based on which we embed our algorithms into the wireless interface drivers.

A. Testbed Setup

The experimental scenario is shown as Fig.5, where 10 StarEast nodes of which six are APs and the rest four act as their respective users. The environment is a lab in FIT building of Tsinghua University, where 8 public IEEE 802.11g APs have been deployed. We tune the frequency of all StarEast nodes to channel 11, where two public APs work at. To decrease the impact of the public APs on the experimental results, all experiments are taken at mid-night when little public traffic is involved. The main role of the scenario is “User 1”, “AP 1”, “AP 2”, and “AP 3”. Other devices behave as the background.

In MAC layer, the adaptive PCS [5] is implemented, which positively tunes the PCS according to the signal strength and network traffic. Herein, the signal strength comes from the per-frame RSSI value (in dBm) obtained from the (Intel PROWireless 2200BG) driver. Because WLANs employ a single channel in both uplink and downlink, we use the RSSI of the received frames to approximate the channel strength of transmitting link.

The proposed AP association algorithm and the AP selection algorithm are implemented in the driver of the MAC layer. In application layer, we use Iperf [22] developed by the Laboratory for Applied Network Research as the bandwidth measurement tool. To eliminate the impact of TCP retransmission on the final results, only UDP service is considered.

For the purpose of comparison, three configurations are measured for each experiment: Single AP without the adaptive PCS, Single AP with the adaptive PCS, and Multi-AP. For each experiment, except the implemented algorithms all other parameters are the same for the three configurations. The physical data is fixed to 18 Mbps in all experiments, and the default PCS threshold in traditional WLAN is -80dBm. Other parameters follow the IEEE 802.11g standard.

B. Experimental Results

1) AP Association: We first show the AP association results in the association state. In the probe phase, 3 APs around the considered user collect the sequence numbers of received frames and send them to the AC. Then, the AC makes statistics based on the reception state of each AP. In the experiment, we move the 3 APs in a short range so as to obtain different scenarios (10 scenarios are tested), and for each scenario a statistic of the whole association procedure is made. During the association procedure, all background devices work in a saturated state by configuring a 18 Mbps UDP service.

Table I shows statistic results of the 10 scenarios. The value in the table is the frame loss rate. It is observed that the frame loss rate can be improved significantly by employing the adaptive PCS. The gain increases with the number of associated APs, but the incremental speed varies with the scenario. With the proposed MF algorithm (κ = 0.05), we list the selection results in the last column. It is observed that the frame loss rate can be decreased significantly when multiple APs are associated, and the selected results of the proposed MF algorithm approaches to that of associating all APs well but with less APs. In most cases of our experiments, the results show that associating 2 APs can achieve similar performance to that of associating all APs.

2) Uplink Performance: For the evaluation of uplink performance, we configure uplink traffic (from users to APs) only. We first measure the frame loss rate of each AP and Multi-AP selected with MF algorithm. Note that the frame loss rate is very low in the condition without the adaptive PCS because all devices can sense each other. Thus, we concentrate on the scenario with the adaptive PCS. As shown in Fig.6, Multi-AP can decrease the frame
TABLE I:
Experimental results of frame loss rate for different associations

<table>
<thead>
<tr>
<th>Index</th>
<th>AP 1</th>
<th>AP 2</th>
<th>AP 3</th>
<th>AP 1 &amp; 2</th>
<th>AP 2 &amp; 3</th>
<th>AP 1 &amp; 3</th>
<th>AP 1 &amp; 2 &amp; 3</th>
<th>MF selection (κ = 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2186</td>
<td>0.4046</td>
<td>0.1209</td>
<td>0.1209</td>
<td>0.0232</td>
<td>0.0232</td>
<td>0.0232</td>
<td>AP 1.3</td>
</tr>
<tr>
<td>2</td>
<td>0.2629</td>
<td>0.3145</td>
<td>0.1408</td>
<td>0.1408</td>
<td>0.0563</td>
<td>0.0563</td>
<td>0.0563</td>
<td>AP 1.3</td>
</tr>
<tr>
<td>3</td>
<td>0.1226</td>
<td>0.1085</td>
<td>0.4623</td>
<td>0.0377</td>
<td>0.1226</td>
<td>0.0377</td>
<td>0.0377</td>
<td>AP 1.2</td>
</tr>
<tr>
<td>4</td>
<td>0.1408</td>
<td>0.2113</td>
<td>0.1033</td>
<td>0.0610</td>
<td>0.0986</td>
<td>0.0235</td>
<td>0.0188</td>
<td>AP 1.3</td>
</tr>
<tr>
<td>5</td>
<td>0.1878</td>
<td>0.1831</td>
<td>0.0986</td>
<td>0.1408</td>
<td>0.0939</td>
<td>0.0657</td>
<td>0.0657</td>
<td>AP 1.3</td>
</tr>
<tr>
<td>6</td>
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<td>0.4554</td>
<td>0.0516</td>
<td>0.1690</td>
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<tr>
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<td>0.4601</td>
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<td>0.1268</td>
<td>0.0469</td>
<td>0.0469</td>
<td>0.0469</td>
<td>AP 1.3</td>
</tr>
<tr>
<td>8</td>
<td>0.3514</td>
<td>0.3216</td>
<td>0.2828</td>
<td>0.1835</td>
<td>0.1249</td>
<td>0.1425</td>
<td>0.1425</td>
<td>AP 1.2</td>
</tr>
<tr>
<td>9</td>
<td>0.1878</td>
<td>0.1831</td>
<td>0.0986</td>
<td>0.1408</td>
<td>0.0939</td>
<td>0.0657</td>
<td>0.0657</td>
<td>AP 1.3</td>
</tr>
<tr>
<td>10</td>
<td>0.2629</td>
<td>0.2302</td>
<td>0.3239</td>
<td>0.2828</td>
<td>0.2828</td>
<td>0.1249</td>
<td>0.1249</td>
<td>AP 1.3</td>
</tr>
</tbody>
</table>

loss rate significantly. The frame loss rate of an AP varies with time, because it depends on the transmission status of the related hidden terminals. As analyzed above, Multi-AP utilizes the diversity effect of multiple APs to achieve the minimum frame loss rate.

In addition, we compare the throughput performance of different configurations: Single AP without the adaptive PCS, Single AP with the adaptive PCS, and the Multi-AP. The results are plotted in Fig.7. In the experiment of Single AP without the adaptive PCS, all transmitters can sense each other and share the channel fairly. It shows that the considered user obtain 3.5 Mbps throughput stably. In that of Single AP with the adaptive PCS, the AP with the strongest RSSI is selected. Compared to the one without the adaptive PCS, the considered user can obtain higher throughput although the frame loss rate is higher as well (as shown in Fig.6). In addition, the throughput is not stable because it is influenced by the transmission status of hidden terminals. For Multi-AP, the considered user can obtain the maximum throughput in the whole measurement period. Compared to that of Single AP with the adaptive PCS, the throughput gain is 10% – 30%.

3) downlink performance: For the evaluation of downlink performance, we configure downlink traffic (from APs to users) only. Without the adaptive PCS, the throughput of each user is bounded around 3.5 Mbps. To maintain the fairness of comparison, we configure the traffic load of background APs (AP 4, 5, 6) with 3.5 Mbps. In the experiment of Single AP with the adaptive PCS, the AP with the strongest RSSI is selected. As shown in Fig.8, it cannot achieve significant throughput gain because the adaptive PCS brings spatial reuse gain. Through debugging
the testbed, we find that the AP with strongest RSSI is AP 3, which neighbors to AP 4, 5 and 6. The employed adaptive PCS algorithm cannot separate the 4 AP completely. The converged PCS threshold is around -40 dBm, but the RSSI’s for links “AP 3 - AP 4”, “AP 3 - AP 5”, and “AP 3 - AP 6” varies around -40 dBm as well. Thus, in most cases AP 3 shares channel with other 3 APs. Differently, from the figure, it is shown that Multi-AP can achieve significant throughput gain. The reason is that the PCS positively selects the AP with minimum neighboring traffic load for downlink transmissions. By statistic measurement, we find that the PCS selects AP 1 or 2 for downlink transmissions although their RSSI is smaller than that of AP 3.

As mentioned above, the throughput gain in downlink is dependent on the traffic load distribution in neighborhood. Thus, we make an experiment to show the impact of asymmetric traffic load distributions. In this experiment, the traffic loads in AP 5 and 6 are fixed to 3.5 Mbps, and the traffic load of AP 4 varies from 3.5 Mbps to 0.8075 Mbps. The traffic ratio is defined as the ratio of AP 5’s traffic load to AP 4’s traffic load. The experimental results are plotted in Fig.9. It is observed that the throughput over Single AP without the adaptive PCS increases with the traffic ratio, because a higher traffic ratio results in a lower background traffic. The results show that the adaptive PCS can obtain limited throughput gain in the downlink. With the joint effect of the adaptive PCS and the AP selection, Multi-AP brings significant throughput gain (nearly 100%) in asymmetric traffic load, and the throughput gain increases with traffic ratio markedly.

VIII. CONCLUSION

In this paper, we leverage the MAP architecture to improve the performance of adaptive PCS based HD-WLANs. We proposed an AP association, an AP selection algorithm and an ACK management solution. By means of the StarEast platform, we deployed a real MAP network employing the proposed algorithm in a typical HD-WLAN scenario. For the purpose of comparison, the performances of traditional Single AP without or with the adaptive PCS were measured as well. The experimental results showed that MAP can obtained up to 30% throughput gain in uplink and nearly 100% gain in downlink. Moreover, the performance brought by the associated AP set selected with the proposed algorithm can approach to the optimum with a smaller overhead.

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