Leveraging Multi-AP Diversity for Transmission Resilience in Wireless Networks: Architecture and Performance Analysis

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Abstract—With the increasing development of IEEE 802.11 based Wireless Local Area Network (WLAN) devices, large-scale multi-cell WLANs with a high density of users and access points (APs) have emerged widely in various hotspots. Providing resilient data transmission has been a primary challenge for scaling the WLANs because the high density of users and APs results in too many collisions. In this paper, we analyze and point out the defect of the single association mechanism defined in IEEE 802.11 on transmission reliability from a network perspective. Then, we propose a “multi-AP” architecture with which a MAC layer device called an AP Controller (AC) is employed to enable each user to associate and cooperate with multiple APs. In this way, the users can benefit from the diversity effect of multipaths with independent collisions and transmission errors. This paper concentrates on the theoretical analysis of performance comparison between the proposed “Multi-AP” architecture and that in IEEE 802.11. Extensive simulation results show that the proposed “multi-AP” architecture can obtain much better performance in terms of the throughput per user and the total throughput, and the performance gain is position dependent. Moreover, the unfairness issue in traditional WLANs due to capture effect can be alleviated properly in the “multi-AP” framework.

Index Terms—WLAN, wireless multi-AP networks, diversity, fairness.

I. INTRODUCTION

T he past few years have seen a tremendous growth in the deployment of Wireless Local Area Networks (WLANs) conforming to the IEEE 802.11 standard. In [1], the authors showed that large-scale 802.11 WLANs with high density of users and Access Points (APs) have emerged widely in various hotspots.

For large-scale networks, improving the throughput per user is a challenge. Different from cellular systems where centralized MAC schemes (e.g., TDMA, FDMA, CDMA) can be implemented efficiently, IEEE 802.11 WLANs adopt a distributed and contention based CSMA/CA access control scheme, which results in many collisions in high density networks. Due to the limited number of available channels (e.g., only 3 non-overlaid channels in 2.4GHz ISM [25]), IEEE 802.11 cannot scale the network only by frequency multiplexing. Alternatively, WLANs employ spatial reuse [6][7] to make the network capacity scalable, i.e., many neighboring APs work in the same channel and use the physical carrier sensing to alleviate interferences. However, due to essential weakness in resisting interferences, the interference distance in WLANs is always much larger than the distance of a transmitter-receiver pair, and thus a user has to compete for the channel with not only the users associated with the same AP but also those associated with neighboring APs. In this way, the transmission reliability suffers from further decrease due to more collisions.

It is well known that traditional WLANs are of “point-to-multipoint” architecture, with which each AP serves a number of users in a particular area and each user associates with only one AP, usually the nearest one. Although such an architecture can work well in the networks with sparse user distributions, in high density WLANs it is insufficient to meet the requirement of the resilience of transmission due to the following reasons:

1) Capture effect: The capture effect [19][20] makes the users far away from their associated AP suffer more backoffs than others, which results in serious unfairness among users in different positions. Especially in the network with high density, the frequent collisions due to capture may starve the users far away from the AP.

2) Hidden terminal problem: For a network with high density, the hidden terminals exist widely, and thus the collisions due to hidden terminals occurs more frequently than that in sparse networks.

3) Exposed terminal problem: With the Single-Association mechanism, a user cannot successfully initiate a new transmission when its associated AP is captured because it stays within the transmission range of an on-going transmission. In this way, the user becomes an exposed terminal of that transmission though it is outside the exposed range in the traditional sense. To distinguish this from the traditional exposed terminal, this type of exposed terminal is denoted as a type II exposed terminal. In high density networks, there are usually multiple APs in the transmission range of each user, and thus type II exposed terminal problem is more serious than that in sparse networks.

Due to the open feature of wireless environment, in the high density WLANs the frames sent by a user can be successfully
decoded by multiple APs working in the same channel and within its transmission range. By means of this feature, in [2], Miu et al. introduced a Multi-Radio Diversity Combiner (MRDC) to collect the signals received by multiple APs and then jointly decode the frame with a frame combining technique, with which the frame loss due to transmission error can be alleviated. The authors focused on the transmission of a single user, and only transmission error was considered. However, from a network perspective, each user competes for the channel with many neighboring users within its carrier sensing range, and the users outside its carrier sensing range can start new transmissions, which is called spatial reuse. Much research [6][17] has shown that channel contention and spatial reuse, rather than transmission error, are the main factors influencing the performance in throughput. The purpose of our paper is to propose a “Multi-AP” architecture and compare its performance in throughput with the traditional WLANs from a network perspective. Herein, “Multi-AP” means that each user is capable of maintaining multiple associations, and correspondingly the network working in the “Multi-AP” mode is called Wireless Multi-AP Network (WMAPN). Because the WMAPN is a MAC-focused solution, several existing physical solutions, such as multi-radio interfaces, multiple-input multiple-output techniques, beamforming antennas, frame combining techniques [2], and the opportunistic channel selection, etc. can be jointly used to further enhance the performance of the networks as in traditional WLANs.

In WMAPNs, each user is allowed to associate with multiple APs within its transmission range according to a certain rule, and a sent frame can be acknowledged as long as any one of its associated APs successfully decodes the frame. Due to the independence of different links in collisions and transmission errors, the probability that all associated APs fail to decode the frame is much smaller than that in the single AP case. In our previous work [8], we set up an IEEE 802.11b testbed based on Intel PRO/Wireless 2200 MiniPCI card to study such a multi-AP diversity effect. As shown in Fig.1, the packet loss is reduced greatly when multiple APs are employed. High reliability means less resource waste for retransmissions, and thus the system capacity can be improved.

In this paper, we focus on the performance analysis of WMAPNs from a network perspective. Based on the characteristics of WMAPNs, we develop an analytical model, which takes transmission errors, collisions, the capture effect, and the spatial reuse into account, to investigate the relations among throughput, transmission error, user density, traffic load, and position. With the proposed model, we investigate the performance improvement of WMAPNs compared to traditional WLANs, and we illustrate that WMAPNs can alleviate the problems (unfairness due to capture effect, hidden terminal problem, and type II exposed terminal problem) which exist in traditional WLANs.

The rest of this paper is organized as follows. In Section II, we describe and analyze the network architecture and the advantages. Then, Section III is devoted to the theoretical formulation over a general physical model. In Section IV, for regular AP distributions we analyze the performance of throughput density. Extensive simulations are implemented in Section V to support the theoretical results. In Section VI, we give a further discussion to the factors which influence the performance in throughput but are not studied theoretically. Related works on our topic are summarized in Section VII. Finally, the conclusions are drawn in Section VIII.

II. NETWORK ARCHITECTURE AND CRITICAL FEATURES

In this section, we first describe a typical architecture of WMAPN and explain the function of each type of device involved in the architecture. Then, the critical features of WMAPN compared to the traditional WLAN are illuminated. The proposed scheme is a MAC-solution, and all the existing high-layer (TCP/IP, application layer) devices and services can be implemented upon the WMAPN without any modifications. Therefore, only MAC-layer devices are depicted in this paper.

A. Network Architecture

Because the IEEE 802.11 standard only provides a limited number of orthogonal channels (3 in 802.11b/g, and 12 in 802.11a), the signal coverage among many neighboring APs working the same channel has to be overlapped in the practical high density deployment [1]. Devices working different channels cannot communicate with each other, and do not interfere with each other as well. A WMAPN consists of several APs working in the same channel, and each user can sense multiple APs within its carrier sensing range and associate with some of them following a certain AP selection algorithm. A service provider can deploy many WMAPNs in the region by tuning them to different orthogonal channels. Because devices working different orthogonal channels do not interfere with each other, and thus we concentrate on a single WMAPN.

A typical architecture of WMAPN is shown in Fig.2. There are three types of devices in such an architecture. Besides APs and users, another important device is Access Controller (AC), which is the centralized controller and responsible for managing all APs. Generally, there is only one AC. For a large-scale deployment where a large number of APs working

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1In IEEE 802.11a/b/g, the signal-interference-and-noise (SNR) requirement for successful decoding is so high that the number of channels for frequency multiplexing is more than the number of orthogonal channels available.

2In this paper, we assume that only orthogonal channels are used in network deployment.
in the same channel, we can divide the whole network into several small WMAPNs so as to alleviate the load of the AC. In the WMAPN, 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. The basic functionalities of each device are described as follows:

1) AC: The main function of the AC is to make AP selection decision and maintain all association information related to the APs it controls. At the association stage, the AC collects the traffic load distribution of the network and the association requests forwarded by the neighboring APs of the considered user, and then makes AP association decision following a certain rule. In addition, the AC is responsible for managing ACKs so as to avoid ACK collisions. When an AP receives a data frame originated from the user associated with it, the AP will create an ACK request frame including the ID of the data frame and forward it to the AC. The AC selects only one of the APs that decode the same data frame to return the ACK with the rule of FCFS (first come first serve), i.e., the AC only replies the first arrival ACK request points to the considered data frame and ignores other ACK requests for the same data frame.

2) AP: Different from that in traditional WLAN, after receiving an association request the AP in WMAPN will not directly decide whether to admit it. The AP forwards the association request to the AC, and then constructs its own association list according to the association response from the AC. At the data delivery stage, when the AP receives a data frame originated from the user associated with it, it will send an ACK request to the AC. If the AP receives the ACK response, it will send the ACK to the user. Basically, the data rate of current wired link (100-1000Mbps) is much larger than wireless link, and the lengths of ACK request and ACK response are very small (on the order of 10s of bytes). Even if many APs transmit simultaneously to AC (in fact it is nearly impossible, because many APs cannot receive the packet at the same time due to different distances to the considered user), the CSMA/CD mechanism employed in wired link can assure that the time of ACK management is smaller than a SIFS (the interval between the data frame and the ACK frame in traditional WLANs), and thus it will not influence the backoff mechanism of the user.

3) User: The functionalities of the user in the WMAPN are the same to those in traditional WLAN: scanning the beacon frames, sending association requests, delivering data, and receiving ACK. In this way, the multi-AP architecture is transparent for the user, which is one of the most important features of the WMAPN.

The working procedure of WMAPN, which consists of the association procedure and the data delivery procedure, are illustrated in Fig.3. Different from the traditional WLAN, WMAPN needs to employ “ACK request - ACK response” to avoid ACK collisions in the scenario that multiple associated APs received the data frame simultaneously. As described above, the procedure of “ACK request - ACK response” must be finished in a SIFS, which requires the bandwidth of wired link between APs and the AC much be large enough. An alternative solution is to employ No-ACK mechanism defined in IEEE 802.11e to enable APs not to reply ACK after receiving data packets. If a frame loss is detected (by means of frame sequence number), the AC sends a packet-level retransmission request to the user. Then, the user retransmits the packet according to the request. It is a layer 2.5 solution, and it requires some modifications to the driver of users.

B. Critical Features

Be enabling each user to associate with multiple APs and having a central controller to coordinate them, such a WMAPN has several distinct characteristics that are worth noting:

1) The uplink transmissions (from users to APs) can benefit from multiple backup reception, and they are more reliable than those of traditional WLANs, especially in high density network and high fading channel environment.

2) In downlink, the users can obtain multi-AP diversity as well by selecting one associated AP with less traffic load for downlink transmissions.

3) With the help of multiple associations, the WMAPN has inherent advantage to alleviate the hidden terminal and the type II exposed terminal problems described above.

- **Hidden terminal** As shown in Fig.2, if user B associates with AP 5 only, user C will be a hidden terminal of user...
B. Alternatively, in the WMAPN, user B can maintain association with both AP 3 and AP 5. Because user B→AP 3 can work well even user C transmit simultaneously, user C will not be the hidden terminal of user B again.

- **Type II exposed terminal** When user B transmits, all APs within its carrier sensing range are blocked. If user C associates with only AP 5, it will be a type II exposed terminal of user B. Alternatively, if user C associate both AP 5 and AP 6, the data frame can be received successfully by AP 6. Then, user C will not be the type II exposed terminal of user B again.

4) With the help of multiple associations, a seamless mobility is feasible. In the WMAPN, when a user roams in the networks it just cuts the association with bad channel gain and still maintains the other associations. At the same time, through periodically scanning, the user can construct new associations to the APs with good channel gains. In this way, the handover is soft, and the user always has some associations available.

In this paper, we concentrate on theoretical analysis of the performance improvement brought by Multi-AP architecture. The diversity gain in downlink is traffic load related and hard to be clarified, and thus we consider the uplink only. In addition, the fourth feature is protocol related and will be explored in the future protocol design.

III. A General Analytical Model

In this section, we concentrate on the performance analysis of the throughput density in a general model to show the advantage of WMAPNs compared to traditional WLANs.

A. The Physical Model

Consider a large-scale network. The \( j \)-th AP is indexed as \( A_j \) \((1 \leq j \leq M)\) and the \( i \)-th user is indexed as \( U_i \) \((1 \leq i \leq N)\). To simplify our analysis, only uplink from users to APs is considered. Herein, the reference receiving signal is given to investigate the average signal strength at the receiver as a function of the distance between the transmitter and the receiver, i.e.,

\[
P_{U_i,A_j} = \bar{P} \left( \frac{d}{d_{ij}} \right)^\alpha,
\]

where \( \alpha \) is the path loss coefficient, ranging from 2 (free space) to 4 (indoor). \( P_{U_i,A_j} \) denotes the signal strength at \( A_j \) received from \( U_i \). Finally, \( \bar{P} \) is the reference receiving signal strength as measured at the reference distance \( d \) (usually 1 meter). Let \( P_{A_j}(t) \) denote the aggregate energy detected by \( A_j \) at time \( t \), which consists of signal (from intended transmitter), interference (from unexpected transmitter(s)) and noise. Then, we have

\[
P_{A_j}(t) = \sum_{n=1}^{N} P_{U_n,A_j} I_{U_n}(t) + P_N,
\]

where \( P_N \) is the power of the ambient noise, and \( I_{U_n}(t) \) is an indicator function, which is given by

\[I_{U_n}(t) = \begin{cases} 1, & \text{if } U_n \text{ is transmitting at } t \\ 0, & \text{otherwise.} \end{cases}\]

To simplify the analysis, we consider the impacts of collisions and transmission errors on transmission failures separately: collisions are determined by interference only; and when no collisions occur transmission failures are dominated by transmission errors which are determined by the noise. When \( U_i \) is transmitting to \( A_j \) at \( t \), from (3) and (4) the signal-to-interference ratio (SIR) observed at \( A_i \) is given by

\[
\text{SIR}_{i,j}(t) = \frac{P_{U_i,A_j}}{\sum_{n=1,n \neq i}^N P_{U_n,A_j} I_{U_n}(t)} = \frac{d_{ij}^{-\alpha}}{\sum_{n=1,n \neq i}^N d_{n,j}^{-\alpha} I_{U_n}(t)}.
\]

From the theory of collisions, \( A_i \) can decode the frame with high probability of success only if during the transmission time the received SIR always exceeds a threshold denoted by \( \delta \). Then, from (5), we have

\[
\sum_{n=1,n \neq i}^N d_{n,j}^{-\alpha} I_{U_n}(t) \leq D_{ij}^{-\alpha}, \quad \text{if } \forall t \in [t_0, t_0 + T],
\]

where \( D_{i,j} = \delta^{1/\alpha} d_{i,j} \) is generally referred to interference radius, \( t_0 \) is the start transmission point of \( U_i \), and \( T \) is the transmission time of a data frame. Herein, definition of interference radius is based on the assumption that the nearest interfering source dominates the aggregated interference. In this paper, a conservative carrier sensing is employed to make sure the carrier sensing range can cover the interfering

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Effect of channel coding. Practically, $C = \{\text{coding, modulation and demodulation}\}$. In particular, it includes transmission power, transmission distance, channel environment and the employed physical techniques, which dominate the reception. Under this condition, the receiving range keep silent during the considered transmission, if the nearest interfering source can be ignored. Correspondingly, the range of the worst link, and then the effect of the second interfering range keep silent during the considered transmission, is neglected.

By the transmission radius, and the values of $\{C_0, C_1, C_2\}$ are plotted in Fig.4. Herein, the distance has been normalized by the transmission radius, and the values of $\{C_0, C_1, C_2\}$ are set to approach to the experimental results shown in [16]. Because the size of ACK frame is much smaller than that of data frame, compared to that of data frame its FER can be neglected.

B. Throughput Density

For a considered transmission originated by $U_i$, the probability of being decoded successfully is denoted by $P_{\text{s.i}}$, the probability that the transmission fails due to collisions is denoted by $P_{\text{collision.i}}$, and the probability that the transmission fails due to transmission error is denoted by $P_{\text{error.i}}$. We have $P_{\text{s.i}} + P_{\text{collision.i}} + P_{\text{error.i}} = 1$. From [17], the probability that more than two users collide together is very small, and thus we assume that the probability that more than two users collide is zero. When two users collide, the wasted time should be divided by two while calculating the local throughput obtained by each user. In this way, the local throughput derived by $U_i$ is given by $^3$

$$S_{\text{local.i}} = \frac{P_{\text{s.i}} E[P]}{P_{\text{s.i}} E[T_s] + P_{\text{collision.i}} E[T_c]/2 + P_{\text{error.i}} E[T_c]}.$$  \hspace{1cm} (11)

where $E[P]$ denotes the average frame payload size, and $E[T_s]$ and $E[T_c]$ denote the average time that the channel was captured by a successful transmission and a collided transmission, respectively. In the remainder of this subsection, we will investigate and compare the achievable throughput density of the user working in the traditional WLANs and that working in WMAPNs.

1) Throughput density in traditional WLANs: Let $E_{i,j}$ denote the event that no collisions occur when $U_i$ sends a data frame to $A_j$. Correspondingly, $E_{i,j}$ denotes the event that a collision occurs. In traditional WLANs each user associates with only one AP, usually the nearest one, and thus the probability that a transmission originated by $U_i$ fails due to a collision is given by

$$P_{\text{collision.i}} = P(E_{i,m_j}) = 1 - P(E_{i,m_j}),$$  \hspace{1cm} (12)

where $d_{i,m_j} \leq d_{i,j}$ for $1 \leq j \leq M$. Correspondingly, the probability that the transmission fails due to transmission error is given by $P_{\text{error.i}}$ is given by

$$P_{\text{error.i}} = (1-P_{\text{collision.i}})FER(l, d_{i,j}) = P(E_{i,m_j})FER(l, d_{i,j}).$$  \hspace{1cm} (13)

Calculating the successful probability with $P_{\text{s.i}} = 1 - P_{\text{collision.i}} - P_{\text{error.i}}$ and substituting them into (11), we can derive the local throughput directly. Then, the throughput density can be computed with $F = \frac{S_{\text{local.i}}}{\eta}$.

2) Throughput density in WMAPNs: Alternatively, in WMAPNs each user is capable of maintaining multiple associations, and the data frame is considered to be received successfully as long as any one of the associated APs decodes the frame. Let $\Theta_i = \{\theta_1, \theta_2, \ldots, \theta_{\eta_i}\}$ denote the set of APs maintaining associations with $U_i$. Without loss of generality, we assume $d_{i,\theta_1} \leq d_{i,\theta_2} \leq \ldots \leq d_{i,\theta_{\eta_i}}$. Then, the probability that a transmission originated by $U_i$ fails due to collisions is given by

$$P_{\text{collision.i}} = 1 - P(\bigcup_{\theta_j \in \Theta_i} E_{i,\theta_j}),$$  \hspace{1cm} (14)

3In practical system, the time for a collision is in order of millisecond, but a slot time is just several microsecond. Therefore, the impact of the time for idle on the throughput is neglected.
and the successful probability is given by
\[ P_{s,i} = \sum_{\Phi \subseteq \Theta_i} P(\bigcap_{\theta_j \in \Phi} E_{i,\theta_j} \bigcap_{\theta_k \notin \Phi} \bar{E}_{i,\theta_k}) \times (1 - \prod_{\theta_j \in \Phi} \text{FER}(l, d_{i,\theta_j})). \]  
(15)

where \( \bar{\Phi} = \Theta_i - \Phi \).

Then, the probability that the transmission fails due to transmission error can be computed by \( P_{\text{error},i} = 1 - P_{\text{collision},i} - P_{s,i} \). Substituting the expressions above into (11), we can derive the local throughput in WMAPNs.

From the analysis above, the successful probability \( P_{s,i} \) in WMAPNs is always no smaller than that in the traditional WLANs as long as \( m_j \in \Theta_i \), i.e. \( m_j = \Theta_i \) is guaranteed. However, associating more APs does not always result in the enhancement of the throughput density, because that: if \( \exists \theta_m \in \Theta_i \) satisfies \( \bar{E}_{i,\theta_m} \) always results in \( \bar{E}_{i,\theta_m} \), i.e. all users that locate in the interfering range of \( U_i \cdot A_{\theta_m} \), are also covered by the interfering range of \( U_i \cdot A_{\theta_m} \), then associating \( A_{\theta_m} \) does not bring the improvement of the throughput density. In addition, it is observed that the performance improvement depends on the position between each user and the associated APs, the traffic load, and the frame error model (10).

The analysis above shows that the performance of WMAPN is dependent of many factors, such as the position relationship between users and APs, the number of APs associated with the user, and the channel conditions. To quantify the performance gain of WMAPN, in the next section we take two regular topologies as example to compute the performance improvement level compared to the traditional WLAN.

IV. THROUGHPUT DENSITY ANALYSIS OVER REGULAR TOPOLOGY

To quantify the performance improvement degree, in this section we consider two typical regular topologies: a chain topology and a grid topology, and give the numerical analysis for those two topologies. Note that the MAC mechanism we discussed in this paper is CSMA \( p \)-persistent. In [18], the authors illuminated that the \( p \)-persistent closely approximates the standard protocol with the same average backoff window size. Therefore, it is reasonable to infer the behavior of the standard protocol from the analytical results based on the \( p \)-persistent protocol. To simplify the computation, the payload size of data frame is fixed.

A. In a Chain Topology

First, we investigate a chain topology with fixed AP interval as shown in Fig. 5. The distance between neighboring APs is fixed as \( L \). All users are randomly located in a line with uniform probability independent of other users, the user density is \( \lambda \) (users/m²).

Let \( P_n(\gamma) \) denote the probability that there are \( n \) users in a given length \( \gamma \), then we have
\[ P_n(\gamma) = \frac{(\lambda \gamma)^n}{n!} e^{-\lambda \gamma}. \]  
(16)

For the traditional WLANs where each user only associates with the nearest AP, the carrier sensing threshold should be set to satisfy the case that the user locates in the middle of two neighbor APs, i.e. the distance to the nearest AP is \( L/2 \). In traditional WLANs, a conservative carrier sensing threshold is set to eliminate the hidden terminal problems. Under this condition, the optimal carrier sensing radius \( [6] \) is given by \( C = \frac{L}{\pi}(1 + \delta^{1/\alpha}) \). To guarantee the fairness of comparison, the carrier sensing radius in WMAPNs is also set to \( C \).

As shown in Fig. 5, we consider a user which is \( x \) (\( x \leq L/2 \)) away from the nearest AP. From the figure, the distances to two 1st tier neighbor APs (AP 1 and AP 2) are respectively \( x \) and \( L - x \) (the related interfering radiuses are denoted by \( R_1 \) and \( R_2 \), respectively), and the distances to two 2nd tier neighbor APs (AP 3 and AP 4) are respectively \( L + x \) and \( 2L - x \). Because in practical system \( \delta^{1/\alpha} \) is larger than 1 (typical value is 2), \( \delta^{1/\alpha}(L + x) > L + x\delta^{1/\alpha} \) and \( \delta^{1/\alpha}(2L - x) > L + (L - x)\delta^{1/\alpha} \) always hold. In this way, the interfering ranges of AP 3 and AP 4 always cover that of AP 1 and AP 2, respectively. From the discussion in the previous section, associating AP 3 and AP 4 will not bring any gain, and thus we only consider the situation associating with AP 1 and AP 2. Then, the related area is divided into 5 regions:

1) Region I: the overlaid interfering region of AP 1 and AP 2. The simultaneous transmissions in this region can disturb the reception in both AP 1 and AP 2.
2) Region II (III): the interfering region of AP 1 (AP 2) except the overlaid. The simultaneous transmissions in this region just disturb the reception in AP 1 (AP 2).
3) Region IV: the carrier sensing region except the overlaid. The simultaneous transmissions in this region can disturb the reception in both AP 1 and AP 2. The simultaneous transmissions in this region will not disturb the reception in AP 1 and AP 2, but the users in this region cannot start new transmissions during the considered user being transmitting. The users in this region are generally called exposed terminals.
4) Region V: hidden region. The simultaneous transmission in this region can disturb the reception of AP 2, and the users in this region is capable of starting new transmissions to disturb AP 2 while the considered user is transmitting due to it out of the carrier sensing range.

For the chain model, the region is measured with length. With a simple calculation, we obtain the length of each region as follows:
\[ R_{I}(x) = L(\delta^{1/\alpha} - 1); \quad R_{III}(x) = C - x(\delta^{1/\alpha} - 1); \quad R_{II}(x) = (2x - L)\delta^{1/\alpha} + L; \quad R_{IV}(x) = R_{V}(x) = C - x(\delta^{1/\alpha} + 1). \]
From the analysis, the ergodic probability of $E_{1,1}$ is given by

$$P(E_{1,1}) = \lim_{t \to \infty} \prod_{\text{users in Region I&II}} P(I_u(t) = 0)$$

$$= \sum_{n=0}^{\infty} P_n[R_l(x) + R_{II}(x)](1 - p)^n$$

$$= e^{-2p\lambda[R_l(x)+R_{II}(x)]}. \quad (17)$$

The condition that $E_{1,2}$ occurs is that there are no simultaneous transmissions in Region I&III and no concurrent transmissions in Region V. No concurrent transmissions means that all users in Region V keep idle in both the last data frame transmit interval and the current interval. From the principle of CSMA/CA, if a user starts a transmission, all users within the related carrier sensing range will not start new transmissions. Therefore, the probability that there are no concurrent transmissions in the Region V during the considered transmission is given by $\max\{0, 1 - R_V(x)/C\}$. Consequently, we have

$$P(E_{1,2}) = e^{-2p\lambda[R_l(x)+R_{II}(x)]} \times \max\{0, 1 - R_V(x)/C\}. \quad (18)$$

For the traditional WLANs, from (12) and (13) we have

$$\begin{cases} P_{\text{collision,1}} = 1 - e^{-2p\lambda[R_l(x)+R_{II}(x)]}, \\ P_{\text{error,1}} = e^{-2p\lambda[R_l(x)+R_{II}(x)]} \cdot \text{FER}(l, x). \end{cases} \quad (19)$$

Substituting them into (11), we can derive the local throughput, and then the throughput density can be obtained with $\eta = 2$.

Alternatively, for WMAPNs, the probability that the transmission fails due to collisions is given by

$$P_{\text{collision,1}}(x) = 1 - P(E_{1,1} \cup E_{1,2})$$

$$= 1 - P(E_{1,1}) - P(E_{1,2} \cap E_{1,2})$$

$$= 1 - e^{-p\lambda[R_l(x)+R_{II}(x)]} \times \begin{cases} 1 - e^{-p\lambda R_l(x)} & x \leq \frac{L(1 - \delta^{-1/\alpha})}{2}, \\ e^{-p\lambda R_{II}(x)} [1 - \left(1 - e^{-p\lambda R_{II}(x)}\right)] & \frac{L(1 - \delta^{-1/\alpha})}{2} < x \leq \frac{L}{2}. \end{cases} \quad (20)$$

Herein, when $x \leq \frac{L(1 - \delta^{-1/\alpha})}{2}$, the interfering range of AP 1 is completely covered by that of AP 2, and thus the collision probability is the same to that in the traditional WLANs. In addition, from (15) we can deduce the successful probability as

$$P_{ss,1}(x) = P(E_{1,1} \cup E_{1,2})[1 - \text{FER}(l, x) \cdot \text{FER}(l, L - x)] + P(E_{1,1} \cap E_{1,2})[1 - \text{FER}(l, x)] + P(E_{1,2} \cap E_{1,1})[1 - \text{FER}(l, L - x)], \quad (21)$$

**Table I**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical header</td>
<td>24</td>
</tr>
<tr>
<td>MAC header</td>
<td>34</td>
</tr>
<tr>
<td>ACK</td>
<td>14</td>
</tr>
<tr>
<td>SIFS time</td>
<td>10</td>
</tr>
<tr>
<td>Slot time</td>
<td>20</td>
</tr>
<tr>
<td>DIFS time</td>
<td>50</td>
</tr>
<tr>
<td>Payload</td>
<td>1024</td>
</tr>
<tr>
<td>$C_0$</td>
<td>0.00005</td>
</tr>
<tr>
<td>$C_1$</td>
<td>0.0625</td>
</tr>
<tr>
<td>$C_2$</td>
<td>1</td>
</tr>
</tbody>
</table>

**Fig. 6.** PIR versus position in the chain topology.

$$P(E_{1,1} \cup E_{1,2}) = 1 - P_{\text{collision,1}}(x), \quad P(E_{1,1} \cap E_{1,2}) = e^{-p\lambda[R_l(x)+R_{II}(x)]} \left[1 - e^{-p\lambda R_{II}(x)} \left(1 - \frac{R_V(x)}{C}\right)\right]$$

Then, we compute the probability that the transmission fails due to transmission error by $P_{\text{error,1}}(x) = 1 - P_{\text{collision,1}}(x) - P_{ss,1}$. Finally, substituting them into (11), we obtain the local throughput achieved in WMAPNs. To better clarify the performance improvement, we evaluate the performance enhancement by a Performance Improvement Ratio (PIR), which is defined as

$$\text{PIR} = \frac{\text{Throughput density achieved in the WMAPNs}}{\text{Throughput density achieved in the traditional WLANs}}. \quad (22)$$

From the analysis above, it is obviously that PIR varies with $x$. With the parameters shown in Table I, we numerically compute the PIR for various user density and plot the results in Fig.6. The parameters for the FER model is the same to that
used in Fig.4, and the distance is normalized with $L = 1$. From the figure, it is observed that the PIR increases with $x$ (the distance to the nearest AP) and $p$ (the transmit probability). From Fig.5, the interfering radius of “user-AP 1” is $\delta^{1/\alpha} x$, and thus the collisions in AP 1 increase with $x$. For WMAPNs where the user associates both AP 1 and AP 2, the increment of $x$ reduces the collisions in AP 2, and thus the user can obtain better reliability from AP 2. When the user locates in the middle of two neighbor APs, i.e. $x = 0.5$, the user derives the maximum gain from the multiple associations. In addition, the increment of $p$ results in more collisions in AP 1, and thus it also leads to the increment of the PIR. From the depiction in Section I, the capture effect leads to serious unfairness for the user located far away APs, which means that the performance of these users needs to be improved. WMAPNs enhance the performance of the users far away APs without depress the user close to APs, and thus properly alleviate the unfairness due to capture effect.

B. In a Grid Topology

For a grid topology as shown in Fig.7, all APs are distributed with a square structure, and the distance of neighbor APs is fixed to $L$. We consider a large network, where all users are randomly located with uniform probability independent of other users. The user density is $\lambda$. Then, from the famous Stirling’s formula proved by Robbins, the probability distribution function for the number of users within area $a$ is given by

$$P_n(a) = \frac{(\lambda a)^n}{n!} e^{-\lambda a}. \quad (23)$$

If the network works as the traditional WLANs, i.e. each user only associates with the nearest AP, from the considered topology the maximum “user-associated AP” distance is $\sqrt{2L}/2$. Therefore, with conservative carrier sensing, the optimal carrier sensing radius [6] is given by $C = \sqrt{2L}/2(\delta^{1/\alpha} + 1)$. To guarantee the fairness of comparison, the carrier sensing radius in WMAPNs is also set to $C$.

From the analysis in Section III, the throughput density computation of WMAPNs involves the solution to overlaid area of multiple interfering range. Unfortunately, the solution to the area overlaid by more than two circle is geometrically too complex to derive a closed-form expression. Therefore, we only consider a simple case that each user associates with the nearest two APs. In this way, from the symmetry of the APs distribution, we only consider the user located in the region marked with border line. For the considered user, the potential APs should be AP 1 and AP 2. To clarify the presentation, we build a 2-dimension coordinate with AP 1 as the origin, and the position of the considered user refers to $(x, y)$. Then, similar to the analysis in the chain model, in such a condition the related area is divided into 5 regions as shown in Fig.7. The area of each region can be calculated with geometrical methods. Herein, we represent their area as $R_l(x, y)$, $R_{ll}(x, y)$, $R_{lll}(x, y)$, $R_{lv}(x, y)$, and $R_v(x, y)$, respectively.

Similar to the analysis in the chain topology, for the traditional WLANs, from (12) and (13) we have

$$\begin{align*}
\{ P_{\text{collision},1}(x, y) &= 1 - P(E_{1,1}) = 1 - e^{-p\lambda R_l(x, y)+R_{ll}(x, y)} \\
P_{\text{error},1}(x, y) &= e^{-p\lambda R_l(x, y)+R_{ll}(x, y)} \times \text{FER}(l, r_1), \quad (24) \end{align*}$$

where $r_1 = \sqrt{x^2 + y^2}$ is the distance between the considered user and AP 1. Substituting them into (11), we can derive the local throughput, and then the throughput density can be obtained with $\eta_{\text{WMAPN}} (\eta = 6)$.

Alternatively, for WMAPNs the probability that the transmission fails due to collisions is given by

$$\begin{align*}
P_{\text{collision*,1}}(x, y) &= \left\{ \begin{array}{ll}
1 - e^{-p\lambda R_l(x, y)+R_{ll}(x, y)} , & \\
\sqrt{(L - x)^2 + y^2} - \sqrt{x^2 + y^2} & \geq \frac{L}{\delta^{1/\alpha}}, \\
1 - e^{-p\lambda R_l(x, y)}(V_1 + V_2) & - \sqrt{x^2 + y^2} \geq \frac{L}{\delta^{1/\alpha}}, \quad \text{else}, \quad \text{(25)}
\end{array} \right.
\end{align*}$$

where $V_1 = e^{-p\lambda R_{lll}(x, y)}$ and $V_2 = e^{-p\lambda R_{lll}(x, y)} \times \max\{0, 1 - 2R_l(x, y)/\pi\}$. Herein, when $\sqrt{(L - x)^2 + y^2} - \sqrt{x^2 + y^2} \geq \frac{L}{\delta^{1/\alpha}}$, the interfering region of AP 1 is completely covered by that of AP 2, and thus the collision probability is the same to that in the traditional WLANs. In addition, from (15) we can derive the successful probability as follows

$$\begin{align*}
P_{s*,1}(x, y) &= P(E_{1,1} \cup E_{1,2})[1 - \text{FER}(l, r_1)\times \text{FER}(l, r_2)] \\
&= P(E_{1,1} \cup E_{1,2})[1 - \text{FER}(l, r_1)] + P(E_{1,2})[1 - \text{FER}(l, r_2)], \quad \text{(26)}
\end{align*}$$

where $r_2 = \sqrt{(L - x)^2 + y^2}$. Then, substituting them into (11), we can obtain the local throughput in WMAPNs, and then the throughput density can be obtained with $\eta_{\text{WMAPN}} (\eta = 6)$.

To better clarify the performance improvement, with the parameters shown in Table.I we numerically compute the PIR for $\lambda = 8$ and plot the results in Fig.8. The distance is normalized with $L = 1$. From the figure, it is observed that PIR is always larger than 1, i.e. WMAPNs always outperform the traditional WLANs in terms of throughput density. When the user is close to the AP, WMAPNs cannot get marked gain from the multiple associations because that the fail probability of the nearest AP is already very small. However, when
the user locates in the middle region of multiple neighbor APs, multiple associations can improve the throughput density significantly. In this way, for the grid topology WMAPNs can alleviate the unfairness issue due to capture effect still.

V. SIMULATION RESULTS

In this section, we take IEEE 802.11b protocol for example to evaluate the performance of WMAPNs compared to the traditional WLANs in regular topologies with NS-2 [24] simulator. The characteristics of physical layer and MAC layer used in the simulations are listed in Table I. For each simulation scenario, the simulation time is 300 seconds, and results are obtained via averaging values from 10 different runs with different seeds.

A. In the chain topology

For the simulation over chain topology, the considered topology is shown as Fig.5. The distance between neighbor APs is normalized as $L = 1$ (unit length). Correspondingly, the carrier sensing radius is set to $\frac{1}{2}(1 + \delta^{1/\alpha}) = 1.5$. The total number of users are 100. For each randomly obtained topology, we run the simulations following the rules of the traditional WLANs and WMAPNs, respectively.

For a given user density, we simulate the networks and randomly select 8 users to observe the throughput improvement. The selected users are sorted in the reverse order of the distance to the nearest AP and are indexed from 1 to 8. The results are plotted in Fig.9, where for each user density the frontal row is the results of the traditional WLANs and the back one is those of WMAPNs. It is observed that the throughput gain of WMAPNs increases with the distance to the nearest AP and the user density. For the users close to APs, WMAPNs cannot bring obvious throughput gain, but the users locate in the middle region of neighbor APs can benefit from WMAPNs significantly. This trend approaches to the variation of the PIR properly, which proves WMAPNs can alleviate the unfairness issue due to capture effect.

B. In the grid topology

For the simulation over chain topology, the considered topology is shown as Fig.7. The distance between neighbor APs is normalized to 1 (unit length). The carrier sensing radius is set to $\frac{\sqrt{2}}{2}(1 + \delta^{1/\alpha}) = 2.12$. The total number of users are 200.

For a given user density, we simulate the networks and randomly select 8 users to observe the throughput improvement. The selected users are sorted in the reverse order of the distance to the nearest AP and are indexed from 1 to 8. From Fig.10, it is observed that the throughput gain of WMAPNs increases with the distance to the nearest AP and the user density as analyzed above, which approaches to the variation of the PIR analyzed above properly. In addition, it is observed that for traditional WLANs the throughput decreases with the distance to the nearest AP and the decrease speed increases with the user density, which is the unfairness issue explained above. In WMAPNs, the users far away APs benefit more gain from the multi-AP architecture, and it is shown that the unfairness is alleviated markedly.

To better clarify the relationship between position and performance improvement level, in Fig.11 we show the regions for different performance improvement level. Herein, throughput improvement ratio (TIR) is defined as

$$TIR = \frac{S_{\text{WMAPNs}} - S_{\text{WLANs}}}{S_{\text{WLANs}}}.$$  \hspace{1cm} (27)

where $S_{\text{WLANs}}$ is the throughput obtained in the WLANs, and $S_{\text{WMAPNs}}$ is the throughput obtained in WMAPNs. From the figure, it is observed that the performance gain increases with...
the scope of this paper. The AP deployment. Characterizing this dependence is beyond the performance gains in fact depend strongly on the density of can obtain marked diversity gain from multiple associations. Due to the space limitation, we did not investigate the effect of “ACK block” on the local throughput. Herein, “ACK block” refers to the event that the data frame is received successfully but the ACK frame is not returned. In fact, if the “ACK block” is considered, the performance gap between WMAPNs and traditional WLANs will be larger.

We take the topology shown in Fig. 7 for example to illustrate the impact of “ACK block”. When user 1 transmits, AP 3 cannot send any frames since it is in the carrier sensing range. Without loss of generality, it is assumed that AP 3 is the associated AP of user 2. Because user 2 is out of the carrier sensing range of user 1, it probably starts a new transmission to AP 3. If user 1 is still transmitting at the end of the data transmission of user 2, AP 3 will not return the ACK frame to the user 2 due to it being in the carrier sensing range of user 1, i.e. the ACK frame is blocked. Due to the ACK block, the transmission of “user 2 - AP 3” fails although there are no collisions and transmission error occur. Different from traditional WLANs, WMAPNs can provide multiple associations, with which the AC can select one of the associated APs that are out of the carrier sensing ranges of ongoing transmissions to return the ACK frame. The reliability of transmissions can be improved further, and WMAPNs get more performance gain compared to the traditional WLANs.

In addition, the AP selection is a key problem for WMAPNs, which determines the performance gain directly. The optimal AP selection algorithm should consider the joint effect of the positions and traffic loads of neighboring APs, and is very complex. Due to the limited space, a detailed AP selection algorithm is out of scope of this paper, and will be investigated in the future work.

VI. FURTHER DISCUSSIONS

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VII. RELATED WORKS

With increasingly development of network scale, much attention has been attracted to the schemes for multi-cell networks. In this area, the existing schemes can be categorized into two classes. The first class of schemes are generally called opportunistic scheduling schemes [3][4][5], which positively exploit the variation of wireless fading channel to increase the one-hop transmission rate. The other class of schemes are mainly devoted to enhance the transmission reliability and allow more simultaneous transmissions by means of multiuser MIMO or spatial reuse techniques. Multiuser MIMO technique enables multiple simultaneous transmissions by means of MIMO signal processing, but it entails great physical complexity and power consumption on the users. The related works can be found in [9][10] and the references therein. Alternatively, the key principle of spatial reuse is to adjust the carrier sensing range in terms of the distance of transmitter-receiver to shrink cell size. In this way, with the capture effect more users can survive interference and transmit simultaneously. The typical schemes can be found in [6][7] and the references listed in these papers.

In [12][13], Chandra et.al. proposed a software based approach, called MultiNet, that facilitates simultaneous connections to multiple networks by virtualizing a single wireless card. The wireless card is virtualized by introducing an intermediate layer below IP, which continuously switches the card across multiple networks. MultiNet is capable of providing multiple association 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 [14] and the references therein.

On the theoretical analysis of WLANs, many models have been proposed. Under the perfect channel without transmission error, the authors of [17] developed a Markov chain model, which with the total throughput in a single cell can be computed accurately. Later, under the same assumption the authors in [18] built a p-persistent based model and illuminated that the p-persistent closely approximates the standard protocol with the same average backoff window size. Ma et al. [21] extended the Markov model to consider the effect of hidden terminal problem, which exists widely in the multi-cell networks, but the transmission error was not considered still. To the best of our knowledge, there are no analytical models addressing the joint effect of transmission errors, collisions, and hidden terminals, which we believe is one of the main contributions of this paper.

VIII. CONCLUSIONS

In this paper, we analyzed and pointed out the impact of traditional single association on the transmission reliability in high density WLANs. Based on the analytical results, we proposed and investigated a multi-AP architecture with which the users can obtain a higher transmission reliability from the diversity effect of multi-path with nearly independent collisions and transmission errors. By means of two regular topologies, we quantified the performance improvement of the proposed mechanism compared to the traditional single
The results showed that our mechanism can obtain position-dependent performance gain. The users far away from all neighbor APs can benefit much better with our mechanism, and then the unfairness due to capture effect in traditional single-AP WLAN can be alleviated properly.

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