Applying Opportunistic Medium Access and Multiuser MIMO Techniques in Multi-Channel Multi-Radio WLANs

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***Abstract*—Opportunistic medium access (i.e., multiuser diversity) and MIMO techniques (i.e., multiple-antenna techniques) are two effective ways to achieve a substantial throughput gain in a multiuser wireless system. In this paper, we propose a medium access control (MAC) protocol with opportunistic medium access and multiuser MIMO techniques (MAC-OMA/MM) in Multi-channel Multi-radio Wireless Local Area Networks (WLANs) to explore the utility of the joint design of these two techniques for the challenging MAC design. Specially, in addition to utilizing multiple channels simultaneously and multiple radio transceivers dynamically, multiuser spatial multiplexing and multiuser diversity are employed in each frequency channel to improve system performance. The key ideas of MAC-OMA/MM can be summarized as follows. By utilizing ATIM (Ad-hoc Traffic Indication Message) windows as in IEEE 802.11 power saving mechanism (PSM) under the distributed coordinate function (DCF) mode, user selection and channel negotiation are conducted between the AP and users via ATIM messages on a common channel. Multiuser diversity are employed to opportunistically schedule among multiple candidate users to optimize data transmission. During data exchange, on each frequency channel, the AP can transmit data to two distinct users simultaneously in the downlink with the help of multiuser spatial multiplexing, and two users can concurrently send data to the AP by uplink-downlink duality in the uplink, which creates an extra dimension in spatial domain to further leverage the effect of multiuser diversity and multi-channel gains. Another contribution of this paper is to provide an analytical model to characterize the impact of our protocol on the system throughput and energy efficiency performance. Extensive simulations have been conducted and the results demonstrate that our protocol outperforms existing multi-channel MAC protocols with only minimal additional overhead and minor enhancements to the IEEE 802.11 PSM.**

I. Introduction

Recent years have witnessed growing interests in multi-channel multi-radio wireless networks which can utilize the multiple channels dynamically or simultaneously to improve overall network throughput. With tremendous popularity of various wireless applications[1], the ability of multi-channel networks to cater to a large number of users running applications with high bandwidth and long lifetime requirements becomes increasingly important. The increasing demands have in turn spurred extensive research efforts to provide significant network capacity and high energy efficiency.

Multiple antennas, namely, multiple-input multiple-output (MIMO) techniques, provide an effective way to boost up channel capacity significantly, along with more reliable communications[2]. MIMO systems can offer spatial diversity gain and spatial multiplexing gain[3], [4]. Spatial diversity can be used to combat severe fading and improve reliability of wireless links via carrying duplicate copies of the same information along multiple antennas, particularly useful for compensating against the effect of node mobility[5]. Spatial multiplexing creates an extra dimension in spatial domain, which can carry independent information in multiple data streams. Spatial multiplexing is also applicable to multiuser MIMO systems, namely, multiuser spatial multiplexing. It makes possible to simultaneously communicate with multiple users at high data rates, thus greatly improves system capacity[3]. Thus, it is desirable for a multiuser MIMO system to operate in a spatial multiplexing mode whenever more than one users are active at the same time. Since the co-channel interference reduces the degrees of freedom, smart interference management should also be implemented to efficiently harvest the spatial multiplexing gain.

Another effective way to improve system capacity is to exploit multiuser diversity. Since not all users are likely to experience deep fading at the same time in a multiuser system, the total throughput of the entire multiuser system is resilient to different users. Thus, diversity occurs not only across the antennas within each user, but also across different users. This type of diversity is referred to as multiuser diversity[2]. It lessens the effect of channel variation by exploiting the fact that different users have different instantaneous channel gains to the shared medium[6]. Opportunistic medium access[8] utilizes the physical layer information from multiple users to optimize the medium access control, in which the users with poor channel condition yield the channel access opportunity to the users with favorable channel quality so that the overall network performance can be greatly improved.

The above observations encourage us to consider the MAC design jointly with these advanced techniques for a multi-channel environment. Nowadays, IEEE 802.11 standard has provided multiple non-overlapping channels for use. For example, 14 channels are available for 802.11b with 5MHz apart in frequency[9]. If at least 30MHz apart in frequency spacing is used for efficient interference cancellation, 3 channels are available for concurrent communications[9]. It is also feasible to equip a device with two or more wireless network interface cards (NICs), i.e., multiple radio transceivers, each can independently switch to and transmit/receive data on a separate channel[8]. Our work will be considered in the context of a multi-channel multi-radio WLAN. The main characteristics of the WLAN considered can be summarized as follows. First, there are multiple orthogonal frequency wireless channels with the same bandwidth. Second, each node has multiple half-duplex radio transceivers which enable them to receive from or transmit to different users simultaneously on different channels. Third, each radio transceiver of the AP has a two-antenna configuration while that of each user is configured with a single antenna. Antennas can operate independently and simultaneously on different frequency channels to make each channel a MIMO link[1]. MIMO links are known to provide extremely high spectral efficiencies in multi-channels by simultaneously transmitting multiple independent data streams on the same channel. Finally, we consider both the downlink traffic (from the AP to users) and its dual uplink traffic (from users to the AP), which implies that the traffic originates from one remote user destined to another user will be forwarded by the AP.

In this paper, we propose a novel MAC protocol with opportunistic medium access and multiuser MIMO techniques (MAC-OMA/MM) in Multi-channel Multi-radio WLANs. The key motivation is to leverage multiuser spatial multiplexing and multiuser diversity to optimize data transmission in each frequency

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[1] A MIMO link here corresponds to a frequency channel in which the AP can simultaneously communicate with multiple users both in the downlink and dual uplink with the help of spatial multiplexing in a multiuser system.

channel. In addition to the concurrent use of multiple channels and dynamic assignment of multiple radio transceivers, the extra spatial reuse and opportunistic medium access control provide further improvement on system performance. In particular, the key ideas and main contributions of our work can be summarized as follows. (1) We employ a timing structure similar to that in IEEE 802.11 PSM to divide time into fixed beacon intervals with a small ATIM window at the beginning of each interval to indicate traffic, select users and negotiate channels for the subsequent data exchange. (2) All negotiations are processed on a common channel during ATIM window. Radios and channels are all assigned in a dynamic fashion. (3) During ATIM window, we utilize opportunistic medium access to formulate the problem of finding a schedule to send (or receive) data with the highest data rate as finding a pair of users that can concurrently communicate with the AP at the maximum sum rate among multiple candidate users. (4) During data exchange on each channel, in the downlink of MAC-OMA/MM, by processing data according to the channel state which can be considered as transmit beamforming, the AP can make the data for one user appear as zero at another user such that it can send distinct packets to two users simultaneously. We call such two users a pair of compatible users among the candidate users. In the dual uplink, two compatible users will concurrently transmit data to the AP. (5) Another contribution of our work is to provide an analytical model that characterizes the throughput and energy efficiency performance in a p-persistent CSMA system.

II. Related Work

There has been much work that studied the benefits of different MAC protocols in a multi-channel multi-radio system, see, for example, [8]-[24]. In the following, we briefly discuss those most related to our work, which can be roughly divided into three categories based on their focuses.

A. Channel Allocation and Radio Assignment

Channel allocation and radio assignment have received a considerable amount of attention in recent years[9]-[23]. The schemes of channel allocation can be roughly divided into two categories. In the first category, a dedicated control channel is maintained. In this case, a dedicated radio is usually attached to the control channel. Though it is convenient to communicate using control messages without any pre-negotiation, it may waste network resource when the control overhead is low. In the second category, there is no dedicated control channel. Channel hopping solutions[11] are always employed in this scenario. For radio (i.e., NIC) assignment, there are three main strategies. The first one is static assignment. It assigns each interface to a channel permanently or for long intervals[12]. When the number of NICs is more than the number of channels, it is a simple static assignment. This strategy does not require any special coordination and is particularly suitable for the case when the delay of interface switching is long. The second strategy is dynamic assignment, in which any NIC can be assigned to any channel and can also frequently switch from one channel to another. In this case, two nodes that intend to communicate with each other require a coordination mechanism to ensure that they are on a common channel at some start point[10]. Typically, the coordination mechanism needs all nodes to visit a common "rendezvous" channel periodically. The third strategy named hybrid assignment allows a static assignment for some NICs and a dynamic assignment for other NICs. It can be further classified into two sub-classes. The schemes in the

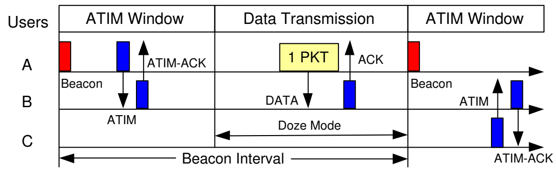

Fig. 1. Basic mechanism of IEEE 802.11 PSM.

first sub-class assign one interface to a common control channel while others dynamically switch among other data channels[13]. The schemes in the second sub-class allow different nodes to assign their "fixed interface" to different channels, thereby ensuring all available channels are occupied while switching the remaining interfaces ensures that communication between any pair of nodes is possible[20]. In fact, channel allocation and radio assignment are mutually dependent and are always jointly considered. Our proposed scheme belongs to the category of the dynamic assignment of multiple radios without a dedicated control channel. By utilizing the timing structure of IEEE 802.11 PSM, all nodes will return to a common channel periodically. The common channel acts as a control channel in the ATIM window and remains to be a data channel during other times.

B. Enhancing IEEE 802.11 PSM

IEEE 802.11 standard provides a power-saving mechanism (PSM) [7] to improve energy efficiency by reducing the idle time as much as possible. The basic idea is illustrated in Fig.1. Time is divided into identical beacon intervals in IEEE 802.11 PSM and all nodes are synchronized by periodical beacon transmissions. At the beginning of each beacon interval, all nodes stay awake for an ATIM window with a constant duration. Node A may transmit an ATIM message to the intended receiver B during the ATIM window if there are some backlogged packets destined to B. Upon receiving the ATIM, node B shall reply an ATIM-ACK. The (re)transmission of the ATIM follows the normal DCF access procedure. At the end of the current ATIM window, any node neither having sent an ATIM nor having received an ATIM containing its own address during the ATIM window (such as node C) shall enter the doze state. Those nodes successful in ATIM exchange during ATIM window shall remain in the awake state until the end of the next ATIM window.

Recent studies have extended the PSM to a multi-channel environment and achieved some evident improvement. So and Vaidya [9], [10] proposed a protocol named multi-channel MAC (MMAC) protocol to exploit the timing structure of IEEE 802.11 PSM to improve throughput and handle the multi-channel hidden terminal problem in multi-hop ad hoc networks. Miller and Vaidya [15] proposed Carrier Sense ATIM (CS-ATIM) that partitions a short carrier sensing period T_{cs} at the beginning of each ATIM window to detect whether there are data packets pending for exchange. Nodes stay awake only for T_{cs} if no packet is to be advertised. Wang, et al. proposed a power-saving multi-radio multi-channel (PSM-MMAC) protocol in [8] to further utilize the sensing carrier period to estimate the number of active links (i.e., node pairs with pending packets for transmission) instead of only determining whether there is pending traffic. With the result of estimation, the ATIM window size and the medium access parameter (e.g., contention window size of the backoff algorithm or the medium access probability of the p-persistent algorithm) can be adjusted accordingly. Our proposed protocol will use the MAC timing structure similar to IEEE 802.11 PSM. In order to keep moderate complexity, we will not consider the adjustable ATIM window and the variable length beacon interval in this paper.

C. Using MIMO Technique and Opportunistic Medium Access

Although MIMO is one of the most promising techniques, it imposes great challenges to the design of upper layer protocols. Sundaresan, et al.[16] proposed a MIMO MAC protocol with closed-loop MIMO and ideal interference cancellation to achieve the spatial multiplexing gain. Hu and Zhang[5] exploited spatial diversity to combat fading and enforce robustness at the presence of user mobility. Moreover, they took a holistic perspectives to investigate the impact of MIMO MAC on routing performance. However, most existing schemes generally target point-to-point MIMO and single channel wireless systems, while in our work we will shift the focus to multiuser MIMO[25]-[27] and multi-channel systems. It exerts the role of multiple antennas in both the uplink (many-to-one) and downlink (one-to-many) of a WLAN by using specific transmitting and receiving strategies while achieving spatial multiplexing gain simultaneously in all frequency channels. When the AP can concurrently communicate with two distinct users both in the uplink and downlink, the spectrum resource is virtually doubled in the ideal case.

Opportunistic medium access algorithms have been developed to utilize the channel variation to enhance system performance. Ji, et al. [1] proposed a Medium Access Diversity (MAD) scheme that leverages the benefits of rate adaptation schemes by aggressively exploiting multiuser diversity over the single channel WLAN. The sender obtains instantaneous channel state information from multiple receivers and selectively transmits data to a receiver with the best channel condition. Most of recent work on diversity in multi-channel systems primarily concentrates on multi-channel diversity. Kanodia, et al.[19] proposed a channel skipping scheme such that if the channel condition is not favorable, mobile nodes can opportunistically skip to other frequency channels with better quality to enable data transmission at a higher rate. Zhang and Zheng[17], [18] propose an opportunistic MAC protocol in multi-channel ad hoc networks that exploits channel variation across multiple channels to boost up system performance. In our study, we will fully take the advantages of the effect of multiuser diversity in both the uplink and the downlink to enhance channel capacity. In particular, in each channel, the AP opportunistically sends out buffered packets to two compatible receivers with the maximum sum rate among multiple candidate users at the same time in the downlink, while two compatible users with the maximum sum rate of the uplink are scheduled to concurrently transmit data to the AP.

III. System Model and Design Overview

A. Multiuser Spatial Multiplexing on a MIMO Link

Consider a multi-channel multi-radio WLAN environment where the AP has multiple radios, each of which is with two antenna configurations and each user also has multiple radios, each of which is configured with a single antenna. This is often a practically interesting case since it is not difficult to equip the AP with multiple antennas. In fact, many wireless routers today have multiple antennas. And another commercially appealing fact is that it does not need new hardware at mobile users. By utilizing the multiple radios and multiple antennas, MIMO links can be realized on all frequency channels. In each frequency channel, the AP communicates with two remote users simultaneously at any given time (i.e., one-to-two downlink and two-to-one uplink). This scenario is described in Fig.2. Without loss of generality, in the following analysis, we focuses on a single frequency channel (i.e., The AP and users are with single radio transceiver).

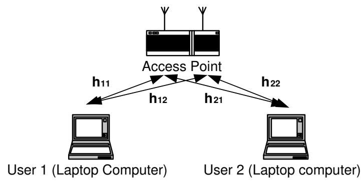

Fig. 2. The AP communicates simultaneously with two users over a single channel.

For simplicity, we use $\mathbf{h}_i$ to denote $[h_{i1}, h_{i2}]^T$ which is the vector form of the complex channel coefficients between the AP's two antennas and the remote user i over a given channel. We first consider the downlink from the AP to two remote users. Let the transmission vector be $\mathbf{x}_{dl}[m] = \tilde{x}_{dl,1}[m]\mathbf{u}_1 + \tilde{x}_{dl,2}[m]\mathbf{u}_2$, where $\tilde{x}_{dl,1}[m]$, $\tilde{x}_{dl,2}[m]$ are complex data destined for user 1 and user 2, $\mathbf{u}_1 = [u_{11}, u_{12}]^T$ and $\mathbf{u}_2 = [u_{21}, u_{22}]^T$ are the transmission signatures for the two users, that is, to send $\tilde{x}_{dl,1}[m]u_{11} + \tilde{x}_{dl,2}[m]u_{21}$ on antenna 1 and to send $\tilde{x}_{dl,1}[m]u_{21} + \tilde{x}_{dl,2}[m]u_{22}$ on antenna 2. We can easily obtain the downlink received signals for the two users

$$\begin{cases} y_{dl,1}[m] = (\mathbf{h}_1^*\mathbf{u}_1)\tilde{x}_{dl,1}[m] + (\mathbf{h}_1^*\mathbf{u}_2)\tilde{x}_{dl,2}[m] + n_{dl}[m] \\ y_{dl,2}[m] = (\mathbf{h}_2^*\mathbf{u}_2)\tilde{x}_{dl,2}[m] + (\mathbf{h}_2^*\mathbf{u}_1)\tilde{x}_{dl,1}[m] + n_{dl}[m] \end{cases}$$

Suppose a proper selection of $\mathbf{u}_1$ and $\mathbf{u}_2$ makes $\mathbf{h}_1^*\mathbf{u}_2 = 0$ and $\mathbf{h}_2^*\mathbf{u}_1 = 0$. Then the two receivers obtain the following signals

$$\begin{cases} y_{dl,1}[m] = (\mathbf{h}_1^*\mathbf{u}_1)\tilde{x}_{dl,1}[m] + n_{dl}[m] \\ y_{dl,2}[m] = (\mathbf{h}_2^*\mathbf{u}_2)\tilde{x}_{dl,2}[m] + n_{dl}[m] \end{cases}$$

In this way, by processing the data according to the channel state, the sender makes the data for one user appear as zero at the other user such that it can send distinct packets to two users simultaneously [26]. Each receiver can simply recover the data by dividing $y_{dl,i}$ by $\mathbf{h}_i^*\mathbf{u}_i$. In other words, the interference introduced by the peer in the simultaneous data transmission is minimized by properly choosing the transmission signatures to maximize each of the SINR's separately.

$\mathbf{u}_1$ can be any vector lies in V_1 which is the space orthogonal to $\mathbf{h}_2$, however, to maximize the received signal strength, $\mathbf{u}_1$ should lie in the same direction as the projection of $\mathbf{h}_1$ onto V_1. $\mathbf{u}_2$ should be similarly chosen[3], [27]. Thus, the normalized $\mathbf{u}_1$ and $\mathbf{u}_2$ can be expressed as follows

$$\mathbf{u}_1 = \frac{\mathbf{h}_1 - \frac{<\mathbf{h}_1,\mathbf{h}_2>}{<\mathbf{h}_2,\mathbf{h}_2>}\cdot\mathbf{h}_2}{\|\mathbf{h}_1 - \frac{<\mathbf{h}_1,\mathbf{h}_2>}{<\mathbf{h}_2,\mathbf{h}_2>}\cdot\mathbf{h}_2\|}, \mathbf{u}_2 = \frac{\mathbf{h}_2 - \frac{<\mathbf{h}_1,\mathbf{h}_2>}{<\mathbf{h}_1,\mathbf{h}_1>}\cdot\mathbf{h}_1}{\|\mathbf{h}_2 - \frac{<\mathbf{h}_1,\mathbf{h}_2>}{<\mathbf{h}_1,\mathbf{h}_1>}\cdot\mathbf{h}_1\|} \quad (1)$$

Hence, the SINR for user k $(k = 1, 2)$ in the downlink is given by

$$SINR_k^{dl} = \frac{P_k\|\mathbf{u}_k^*\mathbf{h}_k\|^2}{N_0 + \sum_{j\neq k} P_j\|\mathbf{u}_j^*\mathbf{h}_k\|^2} = \frac{P_k\|\mathbf{u}_k^*\mathbf{h}_k\|^2}{N_0} \quad (2)$$

where P_k is the transmitting power allocated to user k in the downlink and N_0 is the variance of the Gaussian noise.

Since the total transmitting power is limited, to ensure that the two receivers can be successfully served simultaneously, the following three criteria must be satisfied

$$\begin{cases} P_t \geq P_1 + P_2 \\ SINR_1^{dl} = P_1 \cdot \|\mathbf{u}_1^*\mathbf{h}_1\|^2/N_0 \geq SINR_{th} \\ SINR_2^{dl} = P_2 \cdot \|\mathbf{u}_2^*\mathbf{h}_2\|^2/N_0 \geq SINR_{th} \end{cases} \quad (3)$$

where P_t is the bound on transmitting power, $SINR_1^{dl}$ and $SINR_2^{dl}$ are the downlink SINR of the two users respectively. $SINR_{th}$ are the SINR threshold for the base rate. For any possible split $P_1 + P_2 \leq P_t$ satisfying above equations, the two users are called a pair of compatible users (or compatible pair) and denoted as $1 \bowtie 2$. Each of them is called the compatible peer of the other.

Similarly, when the compatible nodes user 1 and user 2 are the senders simultaneously in the dual uplink, the received vector $\mathbf{y}_{ul}$ at the two receiving antennas of the AP is as follows

$$\mathbf{y}_{ul}[m] = \mathbf{h}_1 x_{ul,1}[m] + \mathbf{h}_2 x_{ul,2}[m] + \mathbf{n}_{ul}[m]$$

where $x_{ul,1}$ and $x_{ul,2}$ are independent data from two users. The AP uses the receiving filters that are the transmission signatures used in the downlink to demodulate the data stream. Since $\mathbf{u}_1^*\mathbf{h}_2 = 0$ and $\mathbf{u}_2^*\mathbf{h}_1 = 0$, the AP can obtain data $\widehat{x}_1$ and $\widehat{x}_2$ as follows

$$\begin{cases} \widehat{x}_1 = \mathbf{u}_1^*\mathbf{y}_{ul}[m] = \mathbf{u}_1^*\mathbf{h}_1 x_{ul,1}[m] + \mathbf{u}_1^*\mathbf{n}_{ul}[m] \\ \widehat{x}_2 = \mathbf{u}_2^*\mathbf{y}_{ul}[m] = \mathbf{u}_2^*\mathbf{h}_2 x_{ul,2}[m] + \mathbf{u}_1^*\mathbf{n}_{ul}[m] \end{cases}$$

Hence, the SINR for user k $(k = 1, 2)$ in the uplink is given by

$$SINR_k^{ul} = \frac{Q_k \|\mathbf{u}_k^*\mathbf{h}_k\|^2}{N_0 + \sum_{j \neq k} Q_j \|\mathbf{u}_k^*\mathbf{h}_j\|^2} = \frac{Q_k \|\mathbf{u}_k^*\mathbf{h}_k\|^2}{N_0}$$

where Q_k is the transmitting power of user k in the uplink. In this case, the individual powers P_k and Q_k to achieve the same SINR's are the same in the downlink and the dual uplink.

The above analysis clearly shows that it is possible to make simultaneous data transmission to distinct users over the same channel with the support of multiuser spatial multiplexing.

B. Design Overview

We implement MAC-OMA/MM at the link layer with the firmware architecture of the AP as shown in Fig.3. MAC-OMA/MM circumvents the complexity introduced to the upper IP layer by exposing only one virtual MAC address in place of the multiple NIC physical MAC addresses as [21]. Multiple interfaces can be dynamically distributed to tune different channels while the default NIC will be assigned to visit a common channel during each ATIM window. Three functional modules in the AP are necessary to support the operations of MAC-OMA/MM. One is the channel coefficient table (CCT) with the size of $C \times K \times 2$, where C and K represent the total number of available channels and users respectively, and 2 stands for the number of transmitting antennas configured in each radio transceiver of the AP. CCT is updated periodically by the AP with the result of channel estimation by means of either passive overhearing or users' active reporting. In our work, we simply assume that the channel state information is available at the AP. The second module is the compatible table (CT) which is a two-dimensional list to record the current compatible peers of each user. CT is refreshed according to the criteria in (1)-(3) once the CCT is updated. The third module is referred to as user table (UT), which maintains the information listed in Table 1. The AP maintains a separate queue for each user and the field "Que-List" represents a candidate queue list that is a subset of queues scheduled by the AP for the current ATIM negotiation. The AP can opportunistically choose two compatible users within the candidate list to achieve multiuser gain. Field "Chan-Occ" is also a list that records the current cumulative occupancy duration of each channel (channels $1 \sim C$). It is initialized at the beginning of each beacon interval and updated once a successful ATIM negotiation completes via overhearing on the common channel during ATIM window. With this information, the AP itself can determine which channel has the maximum residual duration in current interval for data exchange. Field "Neg-Res" records the result of successful ATIM negotiations in pairs.

IV. The Proposed MAC-OMA/MM Protocol

In this section, we present the MAC-OMA/MM protocol in detail. The main components in our protocol span the physical layer, MAC layer and link layer. In essence, we take a cross-layer design approach to optimizing the network performance.

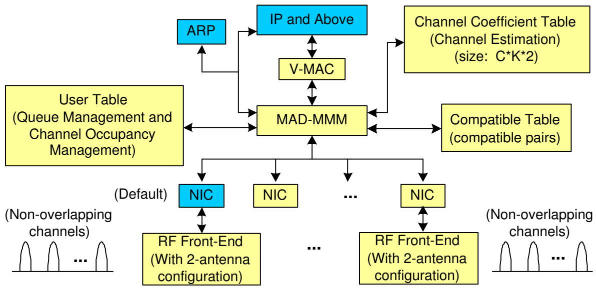

Fig. 3. MAC-OMA/MM firmware architecture in the AP.

TABLE 1

Summary of MAC-OMA/MM User Table in the AP

Field	Notation	Description
User	i	users' index & its IP address
Que-List	$Q[i] \sim Q[i+k]$ ($Q[i] \sim Q[i+k']$)	k (k') candidate traffic queues for current negotiation for downlink (uplink) traffic
Chan-Occ	$T_1^O \sim T_C^O$	the cumulative occupancy duration distributed for successful negotiations
Neg-Res	downlink: e.g. $\{S, D1, D2, c, r, T_s\}$ uplink: e.g. $\{S1, S2, D, c, r, T_s\}$	Negotiation result pairs which indicate the communication pair (source(S) and destination(D)), the assigned channel(c), radio(r), and the estimated start point(T_s)

A. Overview of the MAC-OMA/MM Protocol

Fig.4 gives an overview of the proposed MAC-OMA/MM protocol. The timing structure in the MAC-OMA/MM is similar to the IEEE 802.11 PSM. Time is divided into identical beacon intervals, each of which comprises of two sub-intervals (i.e., ATIM window and data transmission). During the ATIM window, the default NIC in each node will switch to the common channel for negotiations. Note that the common channel is also used for sending data outside the ATIM window. ATIM exchange follows the p-persistent based (or backoff based) CSMA protocol. Nodes involved in the successful negotiations stay awake until the end of next ATIM window while others can turn into doze state for the next data transmission interval.

If the AP captures the chance to access the common channel during the ATIM window, referred to as downlink negotiation, it will negotiate with multiple candidate users for the downlink traffic to obtain multiuser diversity gains. The selection of multiple candidate users (which also represent candidate traffic queues since the AP maintains a separate queue for each user) may be based on QoS requirements of different users or other criteria. Here, we use a simple k-subset round robin policy. The basic idea is that the backlogged users are arranged in a round robin queue. A sliding window of size k advances along the round robin queue with step size 1. For each iteration of the downlink negotiation, k consecutive users within the sliding window are selected as the k candidate users allowed to participate in the current downlink negotiation. The objective of the MAC-OMA/MM scheduler in the AP is to improve channel utilization while limiting the computing overhead, implying that only a subset of users will be considered each time. A larger size subset means more diversity, but also means higher complexity. Thus, k should be set to a moderate value (e.g., $k = 3$ in Fig.4). The AP indicates the addresses of k candidate users, the selected channel and the estimated start point in the Group ATIM message (GATIM). Once receiving the query, the candidate users with available radio transceivers at the estimated start point (called qualified candidate users) will take turns to reply an ACK in the order of the listing rank specified in GATIM. With the knowledge of the compatibility among the

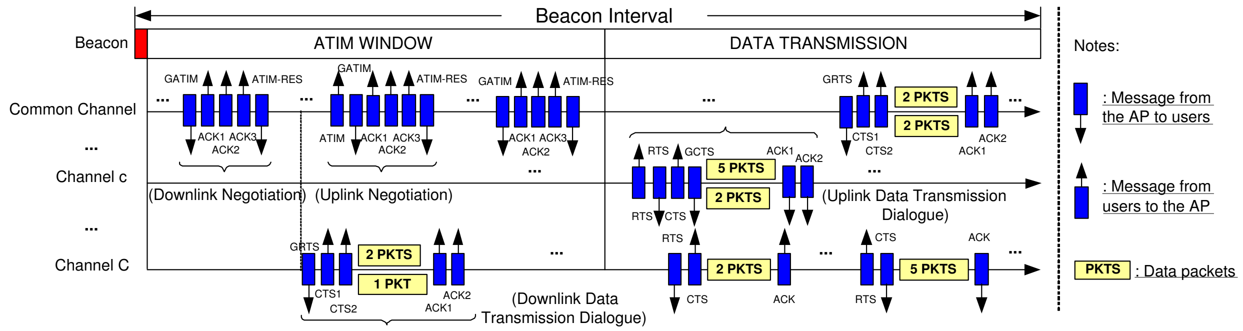

Fig. 4. Overview of the MAC-OMA/MM protocol.

qualified candidate users and the channel state information, the AP finally selects two compatible qualified candidate users with maximum downlink sum rate and notifies them with the ATIM-Reservation (ATIM-RES) message, which is a new type of packet introduced in [9]. The rule for choosing the compatible pair will be explained in detail in the next subsection. When the negotiation completes, the AP and the two compatible users will switch to the selected channel at the estimated start point and start to communicate by exchanging RTS/CTS packets.

Similarly, if a user captures the access chance in the common channel for uplink negotiation, the user will first send an ATIM message to negotiate with the AP for the uplink traffic. Then the AP responds by sending out GATIM to make polling on other k' users (called candidate peers) to inquire whether they currently have backlogged packets. The selection of the k' peers can also simply obey the k'-subset round robin rules. Qualified candidate peers with available radio transceivers will sequentially reply ACKs. By looking up the CT, the AP can decide the compatibility between each qualified candidate peer and the user initializing the request. The AP then selects the most suitable compatible peer for the user complying with the scheduling policy of maximum uplink sum rate. Finally, the AP indicates the two compatible users in ATIM-RES. During data exchange, the two compatible users will concurrently transmit data to the AP in the uplink.

B. Selection of the Compatible Pair and Data Transmission

As mentioned above, during negotiations, the routine for selecting two compatible users among multiple candidate users to serve in the downlink, and selecting the most favorable compatible peer among multiple candidate peers in the uplink is one of the primary design issues in MAC-OMA/MM. Next we will discuss the selection of compatible pair in downlink and uplink negotiations, separately.

In the downlink negotiation, we employ the maximum sum rate scheduling policy to prioritize transmissions, i.e., the AP will preferentially serve the compatible pair with the maximum downlink sum rate. If in the rare case that no compatible pair exists among all the qualified candidate users, the AP can choose to send to only one user with the highest feasible rate. Specifically, among a pool of totally K active users, in each iteration of downlink negotiation during ATIM window, a subset of k candidate users are chosen according to the k-subset round robin scheduling policy. With the channel state information and the replies from the qualified candidate users, the AP checks the compatibility of each pair among the qualified candidate users by looking up the CT and derives transmission signatures of the compatible pairs according to (1). Then the AP searches over all pairs of compatible users (i, j) among the qualified candidate users and any possible power fraction allocation P_i and P_j. The maximum downlink sum rate is achieved by compatible users (i, j) that satisfy

$$\max\left[\log\left(1+\frac{P_i\|\mathbf{u}_i^*\mathbf{h}_i\|^2}{N_0}\right)+\log\left(1+\frac{P_j\|\mathbf{u}_j^*\mathbf{h}_j\|^2}{N_0}\right)\right]$$
$$\text{for } P_i+P_j\le P_t,\ i\bowtie j,\ |i-j|<k,\ i\neq j \text{ and } i,j\in[1,K]$$

Suppose the maximum transmitting power is feasible, i.e., $P_i + P_j = P_t$. Considering the fairness among users, we assume the AP equally allocates the transmission power to the two compatible users, i.e., $P_i = P_j = P_t/2$.

In the downlink data transmission dialogue, the AP will firstly send out an enhanced RTS control packet named Group RTS (GRTS) introduced in [1]. The main difference between GRTS and regular RTS falls in that GRTS has two 6-byte RA (Receiver Address) fields which contain the addresses of the two compatible users. After receiving two CTS's, the AP will simultaneously send multiple data packets to users i and j on the selected channel. With the rate adaptation supported by the physical layer capability of IEEE 802.11, the AP may send data in different rates to the compatible receivers based on the independent channel states. The rate adaptation can be specified as

$$R(SINR_{k,c})=\begin{cases}0, & \text{if } SINR_{k,c}<\beta_0 \text{ or } NAV_{k,c}>0;\\ r_i, & \text{if } \beta_i\le SINR_{k,c}<\beta_{i+1},\\ & i=1,2,\ldots,M-1;\\ r_M, & \text{otherwise.}\end{cases}$$

where $R(SINR_{k,c})$ is the function of the feasible data rate for user k on channel c, M is the size of the set of possible data rates. For instance, in IEEE 802.11b, the possible data rates are $1Mbps$, $2Mbps$, $5.5Mbps$, and $11Mbps$. Hence, M is equal to 4 in this scenario. r_i is the matched achievable data rate tailored to $SINR_{k,c}$, r_M is the highest feasible rate, and β_i is the minimum SINR to achieve a certain bit rate r_i. We choose the SINR thresholds for different data rates based on the settings of $Orinoco^{TM}$ 802.11b card.

Packet bursting is an efficient approach to opportunistically exploiting high quality channels when it occurs via transmission of multiple back-to-back packets[6], [28]. Packet concatenation (PAC)[1] further eliminates many ACKs and SIFSs. As a result, the expected overhead per packet can be reduced and the channel utilization is potentially improved. In our work, we follow the ideas of PAC that the maximum number of continuously transmitted packets for a user in a data transmission dialogue should be $\lfloor R(SINR_{k,c})/r_{base}\rfloor$ in order to maintain the same temporal fairness characteristics as the single rate 802.11, where r_{base} is the base rate of the system. The transmission duration of user k in a data transmission dialogue on channel c is $\lfloor R(SINR_{k,c})/r_{base}\rfloor \cdot E(L)/R(SINR_{k,c})$, where $E(L)$ is the expected value of the packet length. Since there may be a little discrepancy on the transmission durations between two compatible users in a channel, the duration field in data packets should be set to the maximum transmission duration of the two compatible users, which is essential for other nodes in the network to set the network allocation vector (NAV) accordingly.

Similarly, in the uplink negotiation, if user i initiates the request, the AP will assist to poll on k' candidate peers to help select a compatible peer (e.g., user j) to concurrently transmit with user i in the uplink. User i with user j will achieve the maximum uplink sum rate compared to with other compatible peers. Utilizing the uplink-downlink duality, users i and j can use the same transmitting power in the uplink during the data exchange as those allocated to them in the downlink to achieve the same SINR's. The AP uses the receiving filters that are the transmission signatures for users i and j in the downlink to demodulate the data stream as explained in Section III when it receives the data simultaneously from the two compatible users. In the rare case that there is no qualified compatible peers, user i itself will simply send the data to the AP during data exchange.

The procedure of the uplink data transmission follows the same principles as the downlink. Once receiving the RTS from the requesting user, the AP will send out another RTS to help query the selected compatible peer. With the reply from the compatible peer, the AP will notify the two compatible users with Group CTS (GCTS) packet that also has two RA fields. After that, the two compatible users will concurrently transmit uplink to the AP.

C. Channel Allocation and Radio Assignment

Channel allocation and radio assignment are other two important tasks of the negotiations during ATIM window. In our work, the AP dominates the channel selection because it has the complete knowledge of all the available channels and is involved in all uplink and downlink negotiations. For a successful negotiation between the AP and users i and j, if channel c is selected, the estimated occupancy duration is

$$T_c^{i,j} = \max\{ \frac{(PHY+MAC)_{hdr}}{r_{base}} \cdot \left\lfloor \frac{R(SINR_{i,c})}{r_{base}} \right\rfloor + \frac{\left\lfloor \frac{R(SINR_{i,c})}{r_{base}} \right\rfloor \cdot E(L)}{R(SINR_{i,c})}, \\ \frac{(PHY+MAC)_{hdr}}{r_{base}} \cdot \left\lfloor \frac{R(SINR_{j,c})}{r_{base}} \right\rfloor + \frac{\left\lfloor \frac{R(SINR_{j,c})}{r_{base}} \right\rfloor \cdot E(L)}{R(SINR_{j,c})} \}$$

where $(PHY + MAC)_{hdr}$ represents physical and MAC headers that are transmitted at the base rate while the data payloads are transmitted at the achievable data rate. The cumulative occupancy duration of channel c denoted by T_c^O is updated with the value of $T_c^O + T_c^{i,j}$ accordingly. Denote T_c^a as total available duration for data exchange in channel c. Note that the values of T_c^a $(c = 1, \ldots, C)$ are different. The value of the common channel is only the period length of data transmission interval while those of others are the whole beacon interval. In order to balance the traffic loads among different channels, the AP will indicate the preferable channel with the smallest value of T_c^O/T_c^a for the coming successful negotiation. This criterion implies that the channel with the lightest load is always most favorable to be used for data exchange.

As the switching delay has been dramatically reduced to microseconds or even less, we consider dynamically switching a radio from channel to channel within each beacon interval rather than fixing it to a certain channel once it is assigned. This type of assignment has more benefits especially in the situation that the number of radios in each node is less than the number of channels. The principle of radio assignment in our work can be summarized as follows. For each node involved in a negotiation, the NICs that never been distributed in the current beacon interval have the precedence over other NICs to be selected by the node. If no such NICs are available, the node will check whether there is an assigned NIC that will be released and become available at the estimated start point. If there is even no such NIC, the node will refrain from the current negotiation.

V. Performance Modeling

In this section, we develop an analytical model to evaluate the performance of MAC-OMA/MM in terms of system average throughput and energy efficiency. To make our analysis tractable, we first make following assumptions. (1) The AP and all the users always hold backlogged packets and the medium access follows the p-persistent CSMA algorithm. (2) The failure of ATIM negotiations is due to collision or no available radio transceiver in all the candidate users, which implies that fading will not cause loss of ATIM messages. (3) The AP can be equipped with multiple NICs (N_0) equal to the available channels, which means that the AP can always provide available radios without switching. Even though this assumption is not absolutely necessary, it helps reduce the load and complexity of the AP. All the users are equipped with the same number of NICs that are no more than the available channels (i.e., $N_i = N \leq C, i = 1, \ldots, K$). (4) With the information of the estimated start point of each data transmission dialogue, data exchange can be considered collision-free. (5) The AP is located at the center of a disk-like area ϑ with radius γ and a total of K users are randomly distributed in ϑ. For each iteration of the negotiation, k candidate users or k' candidate peers are involved in the downlink and uplink negotiations, respectively.

A. Average Throughput and Energy Efficiency

During ATIM window, the time durations of uplink and downlink negotiations are given by

$$\begin{cases} T_{suc}^{dl} = GATIM + k \cdot ACK + RES + (k+1) \cdot SIFS \\ T_{suc}^{ul} = ATIM + GATIM + k' \cdot ACK + RES + (k'+2) \cdot SIFS \\ T_{fail}^{dl} = GATIM + T_{time\_out} \\ T_{fail}^{ul} = ATIM + GATIM + T_{time\_out} \\ T_{col}^{dl} = GATIM + T_s \\ T_{col}^{ul} = ATIM + T_s \end{cases}$$

where T_{suc}^{dl}, T_{suc}^{ul}, T_{col}^{dl}, T_{col}^{ul}, T_{fail}^{dl} and T_{fail}^{ul} are time durations for successful, collided, or failed (no available NIC) downlink and uplink negotiations, respectively. T_{time_out} is the defined timeout waiting period for replies from candidate users. T_s is the default time-slot size defined in 802.11. Assume each user has available NICs for the currently participating negotiation with probability P_a. For simplicity, we assume each radio in a user is equally likely to be busy during data exchange period. For each user, P_a is the probability that not all its N NICs are busy at the estimated period of data exchange and it can be approximately calculated as follows

$$P_a = 1 - P\{\text{all NICs in a user are not available for the current negotiation}\} \\ \approx 1 - \binom{C}{N} \cdot \left(\frac{2\bar{t}}{T_{int}}\right)^N \cdot \binom{C-N}{1} \cdot \frac{\bar{t}}{T_{int}}$$

where T_{int} is the beacon interval duration and $\bar{t}$ is the approximate time duration for a data transmission dialogue which can be set to $\frac{E(L)}{r_{base}}$. Since the AP and all the users always have buffered packets, in each negotiation, a total of $K + 1$ nodes participate in the contention with the medium access probability p on the common channel. Based on the p-persistent CSMA algorithm, the success probability of downlink and uplink negotiation P_{suc}^{dl} and P_{suc}^{ul}, the collision probability P_{col}^{dl} and P_{col}^{ul}, the failure probability P_{fail}^{dl} and P_{fail}^{ul} and the idle probability P_{id} are

$$\begin{cases} P_{suc}^{dl} = p(1-p)^K \cdot [1-(1-P_a)^k] \\ P_{suc}^{ul} = K \cdot p(1-p)^K [1-(1-P_a)^{k'}] \\ P_{fail}^{dl} = p(1-p)^K \cdot (1-P_a)^k \\ P_{fail}^{ul} = K \cdot p(1-p)^K (1-P_a)^{k'} \\ P_{col}^{dl} = p[1-(1-p)^K] \\ P_{col}^{ul} = (1-p)[1-(1-p)^K - Kp(1-p)^{K-1}] \\ P_{id} = (1-p)^{K+1} \end{cases}$$

Thus, the average total number of negotiations that take place during the ATIM window is

$$\bar{i}_{nego}^{tot} = \frac{T_{ATIM\_W}}{P_{suc}^{dl}T_{suc}^{dl} + P_{suc}^{ul}T_{suc}^{ul} + P_{fail}^{dl}T_{fail}^{dl} + P_{fail}^{ul}T_{fail}^{ul} + P_{col}^{dl}T_{col}^{dl} + P_{col}^{ul}T_{col}^{ul} + P_{id}T_s} \quad (4)$$

where T_{ATIM_W} is the time period of ATIM window and the denominator of (4) represents the average time duration of a negotiation, denoted by $E(T_{nego})$ in the following. Thus, the average number of successful downlink and uplink negotiations denoted by $\bar{i}_{suc}^{dl}$ and $\bar{i}_{suc}^{ul}$ can be written as

$$\bar{i}_{suc}^{dl} = \bar{i}_{nego}^{tot} \cdot P_{suc}^{dl}; \quad \bar{i}_{suc}^{ul} = \bar{i}_{nego}^{tot} \cdot P_{suc}^{ul}$$

As mentioned earlier, the common channel (e.g., channel 1) can be used as a data channel outside the ATIM window. The valid period for data exchange of all the channels can be categorized as

$$\begin{cases} T_{c(c\neq 1)}^{data\_tran} = T_{ATIM\_W} + T_{DATA\_TRAN} - E(T_{nego}) \\ T_1^{data\_tran} = T_{DATA\_TRAN} \end{cases}$$

Denote $P_{data}^{dl\_1}$ as the average probability that there is no compatible pair among k candidate users in a downlink negotiation and the AP will choose one user to serve during data exchange. $P_{data}^{dl\_2}$ represents the average probability that there are compatible pairs and the AP will transmit data to two compatible users simultaneously. $P_{data}^{ul\_1}$ represents the average probability that there is no compatible peer among k' candidate peers in the uplink negotiation and the user initializing the request will simply send data to the AP during data exchange. $P_{data}^{ul\_2}$ represents the probability that there exist compatible peers and two users will concurrently transmit to the AP in the uplink. Denote the average compatible probability between two users as $\bar{P}_c$. The four aforementioned probabilities are given as

$$\begin{cases} P_{data}^{dl\_1} = (1-\bar{P}_c)^{\frac{1}{2}k(k-1)}, & P_{data}^{dl\_2} = 1 - P_{data}^{dl\_1} \\ P_{data}^{ul\_1} = (1-\bar{P}_c)^{\frac{1}{2}k'(k'-1)}, & P_{data}^{ul\_2} = 1 - P_{data}^{ul\_1} \end{cases}$$

Suppose $\bar{S}_{data}^1$ and $\bar{S}_{data}^2$ represent the average number of transmitted packets in a data transmission dialogue that the AP communicates with one user or two compatible users, respectively. The average number of transmitted packets in a downlink or uplink data transmission dialogue n_{data}^{dl} and n_{data}^{ul} are given by

$$\begin{cases} n_{data}^{dl} = P_{data}^{dl\_1} \cdot \bar{S}_{data}^1 + P_{data}^{dl\_2} \cdot \bar{S}_{data}^2 \\ n_{data}^{ul} = P_{data}^{ul\_1} \cdot \bar{S}_{data}^1 + P_{data}^{ul\_2} \cdot \bar{S}_{data}^2 \end{cases}$$

Suppose the physical radio supports M data rates denoted as $r_1, r_2, \ldots, r_M$ ($M = 4$ for 802.11b) and the sender transmits S_{r_m} packets to a receiver in a data transmission dialogue at rate r_m (in our work, $S_{r_m} = \lfloor r_m / r_{base} \rfloor$). In fact, there is a little discrepancy among the transmission durations with different data rates according to the principles of PAC. Hence, we can use $T_{data}^{dl\_1}$, $T_{data}^{dl\_2}$, $T_{data}^{ul\_1}$ and $T_{data}^{ul\_2}$ which are the maximum time durations corresponding to the above four cases that one or two users would communicate with the AP in the downlink and uplink to represent the average time consumption.

$$\begin{cases} T_{data}^{dl\_1} = RTS + CTS + \max\limits_{i\in[1,M]} \left\{ \frac{S_{r_i}E(L)}{r_i} \right\} + ACK + 3SIFS \\ T_{data}^{dl\_2} = GRTS + 2CTS + \max\limits_{i\in[1,M]} \left\{ \frac{S_{r_i}E(L)}{r_i} \right\} + 2ACK + 5SIFS \\ T_{data}^{ul\_1} = RTS + CTS + \max\limits_{i\in[1,M]} \left\{ \frac{S_{r_i}E(L)}{r_i} \right\} + ACK + 3SIFS \\ T_{data}^{ul\_2} = 2RTS + CTS + GCTS + \max\limits_{i\in[1,M]} \left\{ \frac{S_{r_i}E(L)}{r_i} \right\} + 2ACK + 6SIFS \end{cases}$$

If we assume $k = k'$, it is clear that the number of successful uplink negotiations is statistically K times that of the downlink negotiations. Thus, the average time duration and the average number of transmitted data packets for a data transmission dialogue are given

$$\begin{cases} E(\bar{T}_{data}) = \frac{1}{K+1} \cdot \left[P_{data}^{dl\_1} T_{data}^{dl\_1} + P_{data}^{dl\_2} T_{data}^{dl\_2} \right] \\ \qquad + \frac{K}{K+1} \cdot \left[P_{data}^{ul\_1} T_{data}^{ul\_1} + P_{data}^{ul\_2} T_{data}^{ul\_2} \right] \\ E(\bar{n}_{data}) = \frac{1}{K+1} \cdot n_{data}^{dl} + \frac{K}{K+1} \cdot n_{data}^{ul} \end{cases}$$

Denoting i_{data}^{max} as the maximum possible number of data transmission dialogues that can be completed during a beacon interval, we have

$$i_{data}^{max} = \min \left\{ i_{suc}^{dl} + i_{suc}^{ul}, \frac{T_1^{data\_tran}}{E(\bar{T}_{data})} + \sum_{c=2}^{C} \frac{T_c^{data\_tran}}{E(\bar{T}_{data})} \right\}$$

We now obtain the average throughput

$$\bar{S} = \frac{E(\bar{n}_{data}) \cdot E(L) \cdot i_{data}^{max}}{T_{ATIM\_W} + T_{DATA\_TRAN}} \quad (5)$$

Denote PW_{tx}, PW_{rx} and PW_{idle} as the power consumption for the transmitting, receiving and idle states, respectively. $\bar{E}_{ATIM\_W}$ and $\bar{E}_{DATA}$ as the energy consumption for ATIM negotiation and data exchange can be calculated as follows

$$\begin{cases} \bar{E}_{ATIM\_W} = \{(PW_{tx} + K \cdot PW_{rx})(T_{suc}^{dl}P_{suc}^{dl} + T_{suc}^{ul}P_{suc}^{ul} \\ \quad + T_{fail}^{dl}P_{suc}^{dl} + T_{fail}^{ul}P_{fail}^{ul}) + (K+1) \cdot PW_{idle}T_{idle}P_{idle} \\ \quad + \sum_{j=2}^{K+1}[\binom{K+1}{j} p^j (1-p)^{K+1-j} \cdot (j \cdot PW_{tx} \\ \quad + (K+1-j)PW_{rx})] \cdot (T_{col}^{dl}P_{col}^{dl} + T_{col}^{ul}P_{col}^{ul})\} \cdot \bar{i}_{nego}^{tot} \\ \bar{E}_{DATA} = \sum_{i=0}^{K} N_i \cdot PW_{idle} \cdot \frac{1}{C} \sum_{i=1}^{C} T_c^{data\_tran} + \\ \quad \{\frac{1}{K+1} \cdot [(2PW_{tx} + 2PW_{rx} - 3PW_{idle}) \cdot T_{data}^{dl\_2} P_{data}^{dl\_2} \\ \quad + (PW_{tx} + PW_{rx} - 2PW_{idle}) \cdot T_{data}^{dl\_1} P_{data}^{dl\_1}] \\ \quad + \frac{K}{K+1} \cdot [(2PW_{tx} + PW_{rx} - 3PW_{idle}) \cdot T_{data}^{ul\_2} P_{data}^{ul\_2} \\ \quad + (PW_{tx} + PW_{rx} - 2PW_{idle}) \cdot T_{data}^{ul\_1} P_{data}^{ul\_1}]\} \cdot i_{data}^{max} \end{cases}$$

Finally, we can obtain the energy efficiency

$$\bar{E}_{eff} = \frac{\bar{E}_{ATIM\_W} + \bar{E}_{DATA}}{\bar{S} \cdot (T_{ATIM\_W} + T_{DATA\_TRAN})} \quad (6)$$

Here, we do not consider the case of turning a radio into the doze state. Thus, the energy efficiency we derived in the above gives a conservative performance estimation we can achieve with our protocol.

B. *Average Compatible Probability* $\bar{P}_c$

Denote the complex channel coefficient vectors between the AP and two users (e.g., user i and user j) as $\mathbf{h}_i = [a + jb, a' + jb']^T$ and $\mathbf{h}_j = [c + jd, c' + jd']^T$, respectively. For independent Rayleigh channels, a, b, a' and b' are i.i.d Gaussian random variables with the variance $\sigma_{x_i}^2$ and c, d, c' and d' are i.i.d Gaussian random variables with the variance $\sigma_{x_j}^2$.

To obtain the variance (without loss of generality, we derive $\sigma_{x_i}^2$ as an example), denote η_i as the SINR of user i. Here, user i is the only receiver. The AP sends duplicated packets from the two antennas destined to user i with the total transmission power P_t. If free space propagation model is employed, η_i is given by

$$\begin{aligned} \eta_i &= \tfrac{1}{2} P_t \cdot \tfrac{G_t G_r \lambda^2}{(4\pi)^2 L^* x_i^2} \cdot (q^2 + q'^2)/N_0 \\ &= \tfrac{1}{2} P_t \cdot \|\mathbf{h}_i\|^2 / N_0 = \tfrac{1}{2} P_t \cdot (a^2 + b^2 + a'^2 + b'^2)/N_0 \end{aligned} \quad (7)$$

TABLE 2

NUMERICAL RESULTS OF THE CONDITIONAL COMPATIBLE PROBABILITY

(x_i,x_j)	$P_c(c\|x_i,x_j)$	(x_i,x_j)	$P_c(c\|x_i,x_j)$
(50,50)	0.785	(100,150)	0.252
(50,100)	0.537	(100,200)	0.127
(50,150)	0.329	(150,150)	0.161
(50,200)	0.174	(150,200)	0.099
(100,100)	0.421	(200,200)	0.054

where G_t and G_r are the transmitting and receiving antenna gains, λ is the transmission wavelength, L^* is a system loss factor not related to propagation, and q and q' are the small-scale fading parameters of the two Rayleigh channels between the AP's two antennas and the user. With the expectation of (7), we can finally obtain the expression of $\sigma_{x_i}^2$ and $\sigma_{x_j}^2$

$$\sigma_{x_i}^2 = \frac{E(\eta_i)\cdot N_0}{2\cdot P_t}, \qquad \sigma_{x_j}^2 = \frac{E(\eta_j)\cdot N_0}{2\cdot P_t}$$

In fact, $\sigma_{x_i}^2$ and $\sigma_{x_j}^2$ are the ratios of the average receiving power of users i and j to twice of the transmission power. The average receiving power of users i and j is determined by their distances to the AP (i.e., x_i and x_j), respectively.

Denote $P_c(c|x_i,x_j)$ as the conditional compatible probability between user i and user j. It can be expressed as follows according to (3)

$$\begin{aligned} &P_c(c|x_i,x_j) = P(\eta_i \ge \xi, \eta_j \ge \xi) \\ &= P\left(\frac{1/2\cdot P_t\|\mathbf{u}_i^*\mathbf{h}_i\|^2}{N_0} \ge \xi, \frac{1/2\cdot P_t\|\mathbf{u}_j^*\mathbf{h}_j\|^2}{N_0} \ge \xi\right) \\ &= P(f_i(a,b,a',b',c,d,c',d') \ge \xi, f_j(a,b,a',b',c,d,c',d') \ge \xi) \end{aligned}$$

where ξ is the SINR threshold for the base rate, and f_i and f_j are the functions of the channel coefficients, which represent the expressions of η_i and η_j. Due to the complex channel coefficients, it is difficult to derive the exact expression of $P_c(c|x_i,x_j)$. Hence, we employ the numerical Monte Carlo method that is known to be effective to find solutions to mathematical problems that may have many variables and cannot be easily solved. The numerical results of the conditional compatible probability with some given x_i and x_j are shown in Table 2.

In the case that the users are randomly distributed over the disk-like area with radius γ, the locations of all the users are mutually independent and are equally likely to be anywhere over the area ϑ. Denote the distance between the user and the AP as x. For the p.d.f., we have

$$f_X(x) = 2x/\gamma^2 \qquad 0 \le x \le \gamma$$

Now, we can finally obtain the average compatible probability

$$\bar{P}_c = \int_0^\gamma \int_0^\gamma P_c(c|x_i,x_j) f(x_i) f(x_j) dx_i dx_j \tag{8}$$

For a given topology, the average compatible probability can be simplified to

$$\bar{P}_c = \sum_{i,j\in K, i\neq j} P_c(c|x_i,x_j)\cdot \frac{2}{K(K-1)} \tag{9}$$

Next, we give an upper bound for the conditional compatible probability. According to Cauchy-Schwartz inequality, $\|\mathbf{u}_i\mathbf{h}_i\|^2 \le \|\mathbf{u}_i\|^2\|\mathbf{h}_i\|^2 = \|\mathbf{h}_i\|^2$ ($\mathbf{u}_i$ is the current transmitting signature of user i which is a vector with a unit length). The inequality of the conditional compatible probability below will hold.

$$\begin{aligned} &P_c(c|x_i,x_j) \le P\left(\|\mathbf{h}_i\|^2 \ge \frac{2\xi N_0}{P_t}\right)\cdot P\left(\|\mathbf{h}_j\|^2 \ge \frac{2\xi N_0}{P_t}\right) \\ &= P\left(a^2+b^2+a'^2+b'^2 \ge \frac{2\xi N_0}{P_t}\right)\cdot P\left(c^2+d^2+c'^2+d'^2 \ge \frac{2\xi N_0}{P_t}\right) \end{aligned}$$

Let $Y = a^2+b^2+a'^2+b'^2$ and $Z = c^2+d^2+c'^2+d'^2$. Hence, Y and Z follow the chi-square distributions and the conditional compatible probability can be further derived as

TABLE 3

NUMERICAL RESULTS OF THE CONDITIONAL TRANSMISSION RATE PROBABILITY

(x_i,x_j)	$11M$	$5M$	$2M$	(x_i,x_j)	$11M$	$5M$	$2M$
(50,50)	0.770	0.166	0.065	(150,50)	0.162	0.426	0.412
(50,100)	0.759	0.160	0.081	(150,100)	0.190	0.419	0.391
(50,150)	0.786	0.153	0.061	(150,150)	0.157	0.417	0.426
(50,200)	0.767	0.174	0.059	(150,200)	0.180	0.405	0.415
(100,50)	0.417	0.372	0.211	(200,50)	0.059	0.362	0.579
(100,100)	0.382	0.386	0.231	(200,100)	0.058	0.348	0.594
(100,150)	0.394	0.361	0.245	(200,150)	0.060	0.357	0.583
(100,200)	0.384	0.366	0.250	(200,200)	0.058	0.363	0.579

$$\begin{aligned} &P_c(c|x_i,x_j) \le P(Y \ge \tfrac{2\xi N_0}{P_t})\cdot P(Z \ge \tfrac{2\xi N_0}{P_t}) \\ &= \left[1 - \int_0^{\frac{2\xi N_0}{P_t}} \frac{y\cdot\exp(-y/2\sigma_{x_i}^2)}{\sigma_{x_i}^4 2^2\Gamma(2)} dy\right]\left[1 - \int_0^{\frac{2\xi N_0}{P_t}} \frac{z\cdot\exp(-z/2\sigma_{x_j}^2)}{\sigma_{x_j}^4 2^2\Gamma(2)} dz\right] \end{aligned}$$

C. Average Number of Transmitted Packets $\bar{S}_{data}^1$ and $\bar{S}_{data}^2$

During data exchange, our protocol tries to improve the capacity by matching the data rates with the channel conditions. As specified in the rate adaptation, a user can only be assigned a data rate r_m if its estimated SINR is above a threshold η_m ($\eta_1 < \eta_2 < \cdots < \eta_M$). In other words, we introduce rate $r_{M+1} > r_M$ and the corresponding threshold $\eta_{M+1} = \infty$ so that the probability for rate r_{M+1} is 0.

Suppose $P(r_m|x_i)$ denote the conditional probability of using data rate r_m when user i with the distance to the AP x_i is the only sender (or receiver) in a data transmission dialogue.

$$\begin{aligned} P(r_m|x_i) &= P(\eta_m \le \eta_i < \eta_{m+1}) = P\left(\eta_m \le \tfrac{1}{2}P_t\|\mathbf{h}_i\|^2/N_0 < \eta_{m+1}\right) \\ &= P\left(\eta_m \le \tfrac{1}{2}P_t(a^2+b^2+a'^2+b'^2)/N_0 < \eta_{m+1}\right) \\ &= \int_{\frac{2\eta_m N_0}{P_t}}^{\frac{2\eta_{m+1}N_0}{P_t}} \frac{y\cdot\exp(-y/2\sigma_{x_i}^2)}{\sigma_{x_i}^4 2^2\Gamma(2)} dy \end{aligned}$$

Hence, for the case that users are randomly distributed over the disk-like area with radius γ, the average number of transmitted packets in a data transmission dialogue with a single user $\bar{S}_{data}^1$ is

$$\bar{S}_{data}^1 = \int_0^\gamma \left(\Sigma_{m=1}^M P(r_m|x_i) S_{r_m}\right)\cdot f_X(x_i) dx_i \tag{10}$$

When users i and j are compatible users in a data transmission dialogue, let $P_i(r_m|x_i,x_j)$ and $P_j(r_m|x_i,x_j)$ denote their probabilities of using data rate r_m, respectively. Then, $P_i(r_m|x_i,x_j)$ and $P_j(r_m|x_i,x_j)$ can be written as

$$\begin{cases} P_i(r_m|x_i,x_j) = P(\eta_m \le \eta_i < \eta_{m+1}) \\ \qquad = P\left(\eta_m \le \frac{1}{2}P_t\|\mathbf{u}_i^*\mathbf{h}_i\|^2/N_0 < \eta_{m+1}\right) \\ \qquad = P(\eta_m \le f_i(a,b,a',b',c,d,c',d') < \eta_{m+1}) \\ P_j(r_m|x_i,x_j) = P(\eta_m \le f_j(a,b,a',b',c,d,c',d') < \eta_{m+1}) \end{cases}$$

The average number of transmitted packets in a data transmission dialogue with two compatible users $\bar{S}_{data}^2$ is

$$\begin{aligned} \bar{S}_{data}^2 = \textstyle\int_0^\gamma\int_0^\gamma [&\Sigma_{m=1}^M P_i(r_m|x_i,x_j)S_{r_m} + \\ &\Sigma_{m=1}^M P_j(r_m|x_i,x_j)S_{r_m}]\cdot f_X(x_i)f_X(x_j)dx_i dx_j \end{aligned} \tag{11}$$

For a given topology, $\bar{S}_{data}^1$ and $\bar{S}_{data}^2$ can be simplified to

$$\begin{cases} \bar{S}_{data}^1 = \sum_{i\in K}\left(\Sigma_{m=1}^M P(r_m|x_i)S_{r_m}\right)\cdot 1/K \\ \bar{S}_{data}^2 = \sum_{i,j\in K, i\neq j}[\Sigma_{m=1}^M P_i(r_m|x_i,x_j)S_{r_m} + \\ \qquad \Sigma_{m=1}^M P_j(r_m|x_i,x_j)S_{r_m}]\cdot 2/K(K-1) \end{cases} \tag{12}$$

Again, we use numerical Monte Carlo method to obtain some numerical results of the conditional transmission rate probability $P_i(r_m|x_i,x_j)$ as shown in Table 3, where the base rate is set to $2M$.

VI. SIMULATION RESULTS

We have conducted an extensive suite of experiments to evaluate the performance of the proposed MAC-OMA/MM protocol

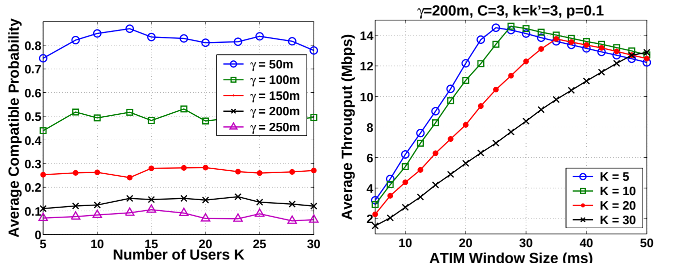

Fig. 5. (a) Compatible probability vs. K. (b) Throughput vs. ATIM window size.

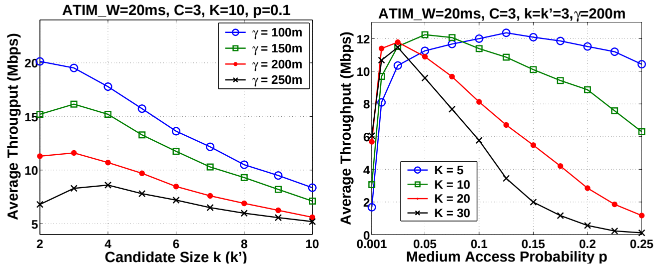

Fig. 6. (a) Throughput vs. k (k'). (b) Throughput vs. p.

and compare it with the MMAC[9] protocol discussed in Section II.

The scenarios and parameters of the simulations are set as follows. We consider a generic network where the AP is located at the center of a disk-like area with radius γ while each user is randomly distributed if no specified topology is indicated. There is a total of C available channels in the system. The AP is equipped with C radio transceivers with 2-antenna configuration and each user has 2 radio transceivers with a single antenna. The AP maintains a separate queue for each user and schedules them in the k-subset round robin manner. The number of candidate users (k) in each downlink negotiation and the number of candidate peers (k') in each uplink negotiation are both set to 3 unless stated otherwise. All the nodes always have backlogged packets with the average packet length of 1000 bytes. The beacon interval is $100ms$ and the ATIM window is fixed to $20ms$. Rate adaptation is employed in the mechanisms we investigated and the base rate is set to $2Mbps$. The output transmitting power of the AP in the network is $15dBm$ and the radio sensitivity for different data rates are configured according to $Orinoco^{TM}$ 802.11b card. The power consumed by a radio in the transmitting, receiving and idle state are set to $1.8W$, $1.3W$ and $1.0W$, respectively. Unless specified otherwise, the medium access probability p is 0.1. The main performance metrics considered in our studies are average network throughput and energy efficiency. Six sets of simulation experiments have been carried out and the results are given below.

A. Average Compatible Probability of the Overall Network

The average compatible probability of the overall network in simulations is defined as the ratio of the number of compatible pairs to the total number of pairs among K active users in the network. Fig.5(a) shows the variation of the average compatible probability when K varies from 5 to 25 in scenarios where the radius γ of the distributed area is equal to $50m$, $100m$, $150m$, $200m$ and $250m$, respectively. We can see that the average compatible probability drops as γ increases. This result is intuitive since the probability of a user with good channel condition drops as γ increases even using the optimal transmit beamforming to completely cancel the interference introduced by the compatible peer. We can also observe that as the increase of the active users, the average compatible probability maintains relatively stable with small fluctuations.

B. Impact of the ATIM Window Size

Fig.5(b) plots the average network throughput of MAC-OMA/MM obtained with the ATIM window size varying from $5ms$ to $50ms$ when K is equal to 5, 10, 20 and 30. γ is set to $200m$ and C is set to 3. Taking the curve with $K = 10$ as an example, the maximum throughput occurs when the ATIM window size is around $27.5ms$. The throughput improvement is largely due to the fact that with this setting of the ATIM window size, the number of successful negotiations can fit into the time duration of data exchange to the most extent. When the ATIM window size is small, the number of successful negotiations is limited. The total time consumption of the corresponding data transmission dialogues is much less compared to the available time for data exchange. Thus, time is wasted during data exchange in each beacon interval, which severely lowers the achievable throughput. On the other hand, when the ATIM window size is large, some negotiations become meaningless and cost time waste because the available time duration for data exchange becomes saturated and it cannot accommodate all successful negotiations. Hence, we can see that when the ATIM window size becomes larger than $27.5ms$, the average throughput gradually declines. These observations are also applicable to the cases when K is equal to other values. In addition, Fig.5(b) also demonstrates that the optimal ATIM window size that can achieve the maximum throughput gradually enlarges as the number of users K increases. This is reasonable since the number of successful ATIM negotiations declines when the collision probability increases as K becomes large.

C. Optimal Values of k and k'

To gain some insight on the effect of multiuser diversity, in this set of simulations, we attempt to experimentally answer the open question that what is the optimal number of the candidate users or peers that the AP should query in the downlink and uplink negotiations. We assume that k and k' have the same value. γ varies from $100m$ to $250m$ to represent different cases of WLANs. The results are plotted in Fig.6(a), from which we can draw some observations. First, the optimal values of k and k' increase with the radius γ. Second, the throughput improvement becomes less obvious when k and k' are larger than 3, and the throughput decreases in all the cases when k and k' are larger than 4. Larger k and k' mean more diversity, but the overhead of the control packet negotiation and especially the computing and comparison complexity introduced to the AP will sharply increase to overshadow the multiuser diversity gain.

D. Impact of the Medium Access Probability p

Fig.6(b) shows the impact of the medium access probability p on the average network throughput when the number of users K is 5, 10, 20, and 30, respectively. The number of the available channels C is 3 and γ is $200m$. It reveals that a large p leads to a high collision probability while a small p makes more time slots idle and causes long time delay, which will both severely dampen the throughput improvement. Thus a proper setting of the medium access probability is crucial to the system performance. The figure also shows that the optimum p decreases as the number of users K increases.

E. Impact of the Radius of the Disk Area γ

Fig.7 depicts the network throughput and energy efficiency of MMAC and MAC-OMA/MM for various radii of the disk area. In this set of experiments, the number of users K is set to 10 and C

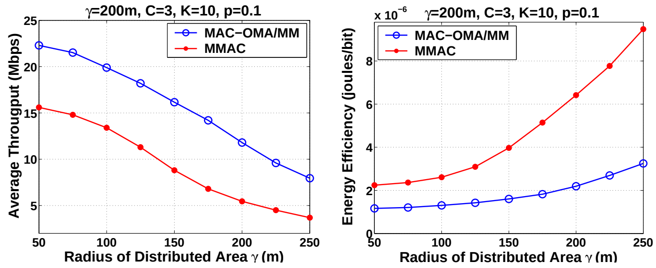

Fig. 7. (a) Throughput vs. radius γ. (b) Energy efficiency vs. radius γ.

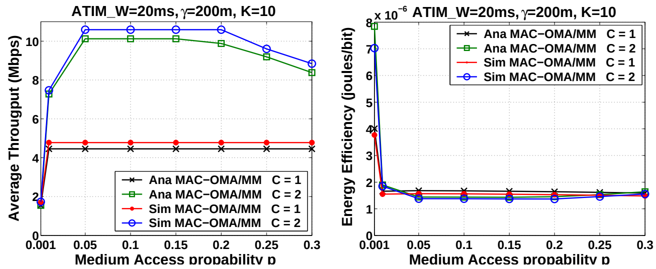

Fig. 8. Simulation results vs. analytical results.

is set to 3. γ varies from $50m$ to $250m$. As the channel condition gets worse (i.e., γ increases), the performance of the both mechanisms degrades. However, we can see that MAC-OMA/MM significantly outperforms MMAC in all cases. In terms of average throughput, MAC-OMA/MM achieves at least 50% improvement over MMAC. Also, MAC-OMA/MM enhances the energy efficiency by up to 180% with respect to MMAC. These improvements are due to the benefits of multiuser diversity gain and simultaneous data transmission with the help of spatial multiplexing in the multiuser network.

F. Simulation Performance vs. Analytical Performance

In this set of experiments, we compare the simulation results with the analytical results of MAC-OMA/MM in terms of the average network throughput and energy efficiency. In order to simplify the computation, we consider a given topology, where 5 aligned users are located $50m \sim 250m$ away from the AP, and every two adjacent users are $50m$ apart. The available channel C is set to 1 and 2, respectively. And 1 or 2 radios are used by each node in the corresponding case. Fig.8 shows that the analytical and simulation results match quite well.

VII. Conclusions

In this paper, we have studied the joint design of opportunistic medium access (multiuser diversity) and MIMO technique (multiuser spatial multiplexing) for multi-channel multi-radio WLANs. This design effectively improves the spectrum utilization via spatial reuse and aggressively optimizes the data transmission by opportunistically serving the users with favorable channel conditions. We have proposed a MAC protocol with opportunistic medium access and multiuser MIMO techniques (MAC-OMA/MM) in Multi-channel Multi-radio WLANs. Besides the concurrent use of multiple channels and dynamic assignment of multiple radio transceivers, two compatible users with maximum sum rate are always selected from multiple candidate users to simultaneously communicate with the AP in each frequency channel, resulting in virtually enriched spectrum resource, improved throughput and high energy efficiency. Another contribution of the paper is to provide an analytical model to characterize the performance of MAC-OMA/MM. Extensive simulation results reveal that our protocol performs much better than other multi-channel MAC protocols with only minimal additional overhead and minor enhancements to the IEEE 802.11 PSM.

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