Medium Access Diversity with Uplink-Downlink Duality and Transmit Beamforming in Multiple-Antenna Wireless Networks

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***Abstract*—In a multiuser wireless system, multiuser diversity for opportunistic scheduling has been extensively studied for high-rate data transmission. In this paper, we propose a novel MAC protocol named Medium Access Diversity with Uplink-Downlink Duality and Transmit Beamforming (MAD-UDD/TB). In addition to aggressively utilizing multiuser gains, it takes advantage of uplink-downlink duality and transmit beamforming, which are the transmitting and receiving strategies used in a multiple antenna environment for simultaneous packet transmissions to multiple distinct users. These techniques effectively leverage the effect of multiuser diversity and greatly improve network throughput by taking into account the opportunistic scheduling among multiple users to prioritize data transmissions. Extensive simulation results show that the proposed protocol achieves much better performance than other medium access diversity and auto rate schemes with minimal additional overhead.**

I. Introduction

In a multiuser wireless communication system with limited bandwidth and power budget, exploiting spatial dimension with multiple antennas to achieve higher data rate has received a considerable amount of attention recently [1]. Multiple antennas provide an effective way to enhance the performance of a wireless system. In addition to allowing spatial multiplexing and providing diversity to each user, multiple antennas make it possible to simultaneously transmit data to or receive data from multiple users at high rate [1], [3]. Multiple antennas create extra dimensions in the spatial domain, which can carry independent information in multiple data streams for concurrent transmissions, thus increase the data rate.

Since not all users are likely to experience deep fading at the same time, the total throughput of the entire multiuser system is resilient to different users. Therefore, 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]. Multiuser diversity lessens the effect of channel variation by exploiting the fact that different users have different instantaneous channel gains for the shared medium [4]. Opportunistic multiuser communication utilizes the physical layer information from multiple users to optimize medium access control. The users with poor channel condition yield the channel access opportunity to the one with better channel quality, thus greatly improves the performance of the entire network.

As mentioned above, the corresponding techniques of multiple antennas and multiuser diversity are two types of efficient ways to improve channel utilization. If the specific transmitting and receiving techniques considered in multiple-antenna wireless environments take into account the scheduling among multiple users to prioritize transmissions, it would further increase the effect of multiuser diversity. This observation is the key motivation of our work. In this paper, we propose a scheme named Medium Access Diversity with Uplink-Downlink Duality and Transmit Beamforming (MAD-UDD/TB). The proposed scheme is presented in the context of Wireless LANs where the Access Point (AP) is equipped with two antennas and each remote user has a single antenna. The scheme can be generalized to the case with an arbitrary number of antennas at both the AP and the remote users. In the downlink of MAD-UDD/TB (from the AP to the remote users), 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 the other user such that it can send distinct packets to two distinct users simultaneously. We call such two users a pair of compatible users and each user is mutually the other's compatible peer. To leverage the effect of multiuser diversity, for each downlink transmission, the AP will select out multiple users as candidate receivers. Since the total transmitting power is limited, not all pairs amongst the candidate receivers are compatible. The AP always transmits data to the pair of compatible users with the maximum sum of downlink data rate among the selected candidate receivers. In the dual uplink (from the remote users to the AP), once a remote user requests to send data to the AP, the AP will schedule to poll on part of the requesting user's compatible peers with backlogged packets and admit the pair with the maximum sum of uplink rate to transmit data simultaneously. We assume that the channel environment is slow changing as compared to the data rate. The AP keeps the channel coefficient vectors of all users that have been reported to it previously and makes update via channel estimation periodically. Our scheme is apparently feasible because it is not difficult to equip the AP with multiple antennas and it can be implemented with relatively minor modifications to the IEEE 802.11 standard.

The rest of this paper is organized as follows. Section II describes the general and special cases of multiple-antenna system model. Section III presents the principles of MAD-UDD/TB. Section IV presents simulation results to evaluate the effect of MAD-UDD/TB on the throughput of wireless LANs. Finally, Section V concludes the paper.

II. Multiple-Antenna System Model

A. The General Case

Consider a wireless LAN environment where the AP has multiple transmitting antennas and each user has a single receiving 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 any new hardware at mobile users. The baseband model of narrowband downlink AP-to-user transmission where the AP has n_t antennas and there are K users with each having a single anten-

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na can be described as follows [1].

$$y_{dl,k}[m] = \mathbf{h}_k^*[m]\mathbf{x}[m] + n_{dl,k}[m], \quad k = 1, 2, \ldots, K \tag{1}$$

where $y_{dl,k}[m]$ is the received signal for user k at time m, and $\mathbf{h}_k^*$ is an n_t-dimensional row vector representing the channel from the AP to user k. For easy analysis, we begin with a time-invariant channel, i.e., $\mathbf{h}_k$ is fixed. $\mathbf{x}[m]$ is an n_t-dimensional vector representing the transmitted signal from the AP, and noise $n_{dl,k}[m] \sim \mathcal{CN}(0, N_0)$ and is i.i.d. in time m.

Denote $\mathbf{u}_1, \mathbf{u}_2, \ldots, \mathbf{u}_K$ as the transmission signatures used for the K users in transmit beamforming [1]. Thus, the transmitted signal is as

$$\mathbf{x}[m] = \sum_{k=1}^{K} \tilde{x}_k[m]\mathbf{u}_k \tag{2}$$

where $\tilde{x}_k[m]$ is the data stream for user k. Substituting in (1), we have the received signal of user k as [1]

$$y_{dl,k}[m] = (\mathbf{h}_k^*\mathbf{u}_k)\tilde{x}_k[m] + \sum_{j \neq k}(\mathbf{h}_k^*\mathbf{u}_j)\tilde{x}_j[m] + n_{dl,k}[m] \tag{3}$$

Hence, the SINR for user k in downlink is given by [1]

$$SINR_k^{dl} = \frac{P_k \|\mathbf{u}_k^*\mathbf{h}_k\|^2}{N_0 + \sum_{j \neq k} P_j \|\mathbf{u}_j^*\mathbf{h}_k\|^2} \tag{4}$$

We rewrite the downlink channel (1) in matrix form as follows

$$\mathbf{y}_{dl}[m] = \mathbf{H}^*\mathbf{x}_{dl}[m] + \mathbf{n}_{dl}[m] \tag{5}$$

where $\mathbf{y}_{dl}[m] = (y_{dl,1}[m], \ldots, y_{dl,K}[m])^T$ is the vector of the received signals at all K users and $\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_K]$ is an n_t by K matrix, $\mathbf{x}_{dl}[m]$ is an n_t-dimensional vector of transmitted signal, and $\mathbf{n}_{dl}[m]$ is an i.i.d. $\mathcal{CN}(0, N_0)$ noise vector.

The uplink channel that is naturally "dual" to the given downlink channel, has K users with each having a single transmitting antenna and the AP equipped with n_t receiving antennas

$$\mathbf{y}_{ul}[m] = \mathbf{H}\mathbf{x}_{ul}[m] + \mathbf{n}_{ul}[m] \tag{6}$$

where $\mathbf{y}_{ul}[m]$ is the vector of aggregated received signals at n_t antennas of the AP, $\mathbf{x}_{ul}[m]$ is the K-dimensional vector of transmitted signals from the K users in the uplink and $\mathbf{n}_{ul}[m]$ is an i.i.d. $\mathcal{CN}(0, N_0)$ noise vector. To demodulate the data stream from the kth user in the uplink, the AP needs to use the received filter $\mathbf{u}_k$, which is the transmission signature for user k in the downlink, i.e., $\hat{x}_k = \mathbf{u}_k^*\mathbf{y}_{ul}$. Therefore, in the dual uplink, the SINR for user k is given by [1]

$$SINR_k^{ul} = \frac{Q_k \|\mathbf{u}_k^*\mathbf{h}_k\|^2}{N_0 + \sum_{j \neq k} Q_j \|\mathbf{u}_k^*\mathbf{h}_j\|^2} \tag{7}$$

where Q_k is the transmitting power of user k. The two dual uplink and downlink systems are shown in Fig. 1.

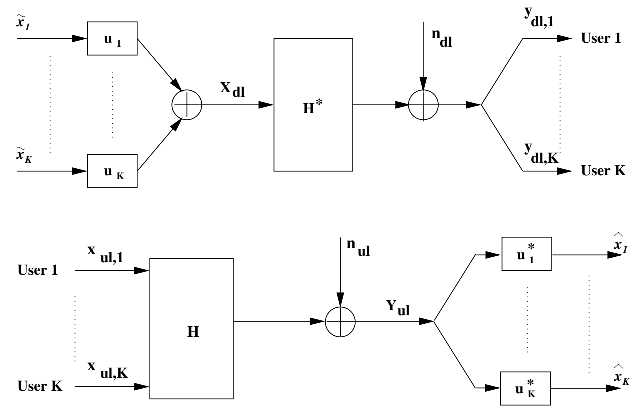

Fig. 1. The downlink and its dual uplink with linear transmitting and receiving strategies.

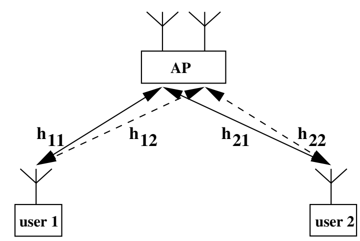

Fig. 2. The AP is equipped with two antennas and each remote user has a single receiving antenna.

B. The Special Case

In our work, we focus on the special case that the AP is equipped with two antennas and each remote user has a single antenna. According to the spatial degrees of freedom, the AP can accommodate two remote users simultaneously at any given time. This scenario is described in Fig. 2.

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. We firstly observe the downlink from the AP to remote users. Let the transmission vector be $\mathbf{x}_{dl}[m] = \tilde{x}_1[m]\mathbf{u}_1 + \tilde{x}_2[m]\mathbf{u}_2$, where $\tilde{x}_1[m]$, $\tilde{x}_2[m]$ are complex data destined for user 1 and user 2, the transmission signatures are $\mathbf{u}_1 = [u_{11}, u_{12}]^T$ and $\mathbf{u}_2 = [u_{21}, u_{22}]^T$, that is, to send $\tilde{x}_1[m]u_{11} + \tilde{x}_2[m]u_{21}$ on antenna 1 and to send $\tilde{x}_1[m]u_{21} + \tilde{x}_2[m]u_{22}$ on antenna 2. We can easily obtain the downlink received signals for the two users as follows

$$y_{dl,1}[m] = (\mathbf{h}_1^*\mathbf{u}_1)\tilde{x}_1[m] + (\mathbf{h}_1^*\mathbf{u}_2)\tilde{x}_2[m] + n_{dl,1}[m] \tag{8}$$
$$y_{dl,2}[m] = (\mathbf{h}_2^*\mathbf{u}_2)\tilde{x}_2[m] + (\mathbf{h}_2^*\mathbf{u}_1)\tilde{x}_1[m] + n_{dl,2}[m] \tag{9}$$

Suppose $\mathbf{h}_1^*\mathbf{u}_2 = 0$ and $\mathbf{h}_2^*\mathbf{u}_1 = 0$. Then the two receivers get

$$y_{dl,1}[m] = (\mathbf{h}_1^*\mathbf{u}_1)\tilde{x}_1[m] + n_{dl,1}[m] \tag{10}$$
$$y_{dl,2}[m] = (\mathbf{h}_2^*\mathbf{u}_2)\tilde{x}_2[m] + n_{dl,2}[m] \tag{11}$$

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 distinct users simultaneously. Each receiver can simply recover the data by dividing y_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.

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$\mathbf{u}_1$ 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. Thus, the normalized $\mathbf{u}_1$ and $\mathbf{u}_2$ can be expressed as follows

$$\mathbf{u}_1 = \frac{\mathbf{h}_1 - \frac{<\mathbf{h}_1,\mathbf{h}_2>}{<\mathbf{h}_2,\mathbf{h}_2>} \cdot \mathbf{h}_2}{\|\mathbf{h}_1 - \frac{<\mathbf{h}_1,\mathbf{h}_2>}{<\mathbf{h}_2,\mathbf{h}_2>} \cdot \mathbf{h}_2\|}, \quad \mathbf{u}_2 = \frac{\mathbf{h}_2 - \frac{<\mathbf{h}_1,\mathbf{h}_2>}{<\mathbf{h}_1,\mathbf{h}_1>} \cdot \mathbf{h}_1}{\|\mathbf{h}_2 - \frac{<\mathbf{h}_1,\mathbf{h}_2>}{<\mathbf{h}_1,\mathbf{h}_1>} \cdot \mathbf{h}_1\|} \tag{12}$$

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

$$SINR_k^{dl} := \frac{P_{tk}\|\mathbf{u}_k^*\mathbf{h}_k\|^2}{N_0 + \sum_{j\neq k} P_{tj}\|\mathbf{u}_j^*\mathbf{h}_k\|^2} = \frac{P_{tk}\|\mathbf{u}_k^*\mathbf{h}_k\|^2}{N_0} \tag{13}$$

where P_{tk} is the transmitting power allocated to user k 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 set of criteria must be satisfied

$$\begin{cases} P_t \geq P_{t1} + P_{t2} \\ P_{r1} = P_{t1} \cdot \|\mathbf{u}_1^*\mathbf{h}_1\|^2 \geq P_{th} \\ P_{r2} = P_{t2} \cdot \|\mathbf{u}_2^*\mathbf{h}_2\|^2 \geq P_{th} \\ SINR_1^{dl} = \frac{P_{t1}\cdot\|\mathbf{u}_1^*\mathbf{h}_1\|^2}{N_0} \geq SINR_{th} \\ SINR_2^{dl} = \frac{P_{t2}\cdot\|\mathbf{u}_2^*\mathbf{h}_2\|^2}{N_0} \geq SINR_{th} \end{cases} \tag{14}$$

where P_t is the bound of transmitting power, P_{r1}, $SINR_1^{dl}$ and P_{r2}, $SINR_2^{dl}$ are receiving power and SINR of the two users respectively, and P_{th}, $SINR_{th}$ are the receiving power and S-INR threshold for the base rate of the system. For any possible split $P_{t1} + P_{t2} \leq P_t$ satisfying above equations, the two users are called a pair of compatible users.

Similarly, when the compatible user 1 and user 2 are the senders simultaneously in the dual uplink, the received vector at the two receiving antennas of the AP is as follows

$$\mathbf{y}_{ul}[m] = \mathbf{h}_1 x_{ul,1}[m] + \mathbf{h}_2 x_{ul,2}[m] + \mathbf{n}_{ul}[m] \tag{15}$$

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 $\mathbf{u}_2^*\mathbf{h}_1 = 0$, finally we can obtain

$$\widehat{x}_1 = \mathbf{u}_1^*\mathbf{y}_{ul}[m] = \mathbf{u}_1^*\mathbf{h}_1 x_{ul,1}[m] + n_{ul}[m] \tag{16}$$
$$\widehat{x}_2 = \mathbf{u}_2^*\mathbf{y}_{ul}[m] = \mathbf{u}_2^*\mathbf{h}_2 x_{ul,2}[m] + n_{ul}[m] \tag{17}$$

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

$$SINR_k^{ul} = \frac{Q_k\|\mathbf{u}_k^*\mathbf{h}_k\|^2}{N_0 + \sum_{j\neq k} Q_j\|\mathbf{u}_k^*\mathbf{h}_j\|^2} = \frac{Q_k\|\mathbf{u}_k^*\mathbf{h}_k\|^2}{N_0} \tag{18}$$

In order to achieve the same SINR, we assume that the transmitting power for an individual user is the same in the downlink and dual uplink [1].

III. MAD-UDD/TB Principle

A. Downlink Transmission

The downlink of MAD-UDD/TB consists of three phases: scheduling, RTS/CTS exchange and data transmission. Components spanning over the link layer, MAC layer and PHY layer are employed to achieve the benefit of the cross-layer design. The basic mechanism of downlink MAD-UDD/TB is shown in Fig. 3.

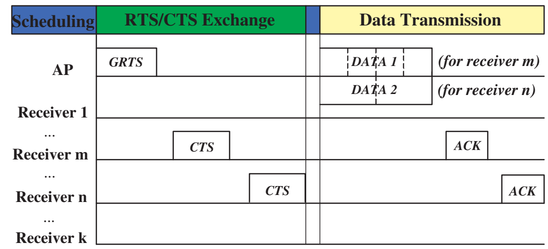

Fig. 3. The downlink of MAD-UDD/TB.

The objective of the MAD-UDD/TB scheduler is to improve channel utilization while limiting the computing overhead, implying that only a subset of receivers will be considered as candidate receivers each time. A larger size of the subset means more diversity, but also means higher complexity. The maximum sum rate scheduling policy is employed in our work to prioritize the transmissions, i.e., the AP will preferentially serve the compatible pair with the maximum sum rate among the candidate receivers. It is assumed that the AP keeps the periodically updated channel coefficient vectors of all users. If in the rare case that no compatible pair exists among all the candidate receivers, the AP can choose to send to only one receiver with the highest feasible rate. Specifically, among a pool of K active users, in each time, a subset of k candidate receivers are chosen. The maximum sum rate is achieved by searching over the pairs of compatible users (i, j) and any possible power fraction allocation P_{ti}, P_{tj} as given below

$$\max \left[\log\left(1 + \frac{P_{ti}\|\mathbf{u}_i^*\mathbf{h}_i\|^2}{N_0}\right) + \log\left(1 + \frac{P_{tj}\|\mathbf{u}_j^*\mathbf{h}_j\|^2}{N_0}\right)\right]$$
$$\text{for } P_{ti} + P_{tj} \leq P_t, \quad i, j = 1, 2, \ldots, k \tag{19}$$

Suppose the maximum transmitting power is feasible, i.e., $P_{ti} + P_{tj} = P_t$. Substitute P_{tj} with $P_{tj} = P_t - P_{ti}$ in (19) and then solve the corresponding quadratic equation to obtain the maximum value. Thus, for a certain pair of compatible users (i, j), the maximum sum rate can be achieved with power allocation as follows

$$\begin{cases} P_{ti} = \frac{P_t\|\mathbf{u}_i^*\mathbf{h}_i\|^2\|\mathbf{u}_j^*\mathbf{h}_j\|^2 + N_0(\|\mathbf{u}_i^*\mathbf{h}_i\|^2 - \|\mathbf{u}_j^*\mathbf{h}_j\|^2)}{2\|\mathbf{u}_i^*\mathbf{h}_i\|^2\|\mathbf{u}_j^*\mathbf{h}_j\|^2} \\ P_{tj} = \frac{P_t\|\mathbf{u}_i^*\mathbf{h}_i\|^2\|\mathbf{u}_j^*\mathbf{h}_j\|^2 - N_0(\|\mathbf{u}_i^*\mathbf{h}_i\|^2 - \|\mathbf{u}_j^*\mathbf{h}_j\|^2)}{2\|\mathbf{u}_i^*\mathbf{h}_i\|^2\|\mathbf{u}_j^*\mathbf{h}_j\|^2} \end{cases} \tag{20}$$

A simple way to implement the maximum sum rate scheduling is to leverage the extra information of maximum sum rate among k candidate receivers on top of the basic round robin scheduling. In this paper, we use this scheme for simplicity.

The use of request-to-send (RTS) and clear-to-send (CTS) control packets as the handshaking signals before actual transmission of the data packet is a well-known distributed channel acquisition mechanism employed by the IEEE 802.11 wireless networks. Once the AP chooses the two compatible receiver-s with maximum sum rate, it will send the destined receivers RTS. We adopt the enhanced RTS control packet named Group RTS (GRTS) introduced in [5] (see Fig. 4(a)). The main d-ifference between GRTS and regular RTS falls in two aspects.

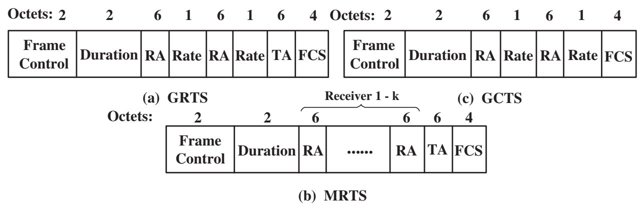

Fig. 4. MAC frame formats used in MAD-UDD/TB.

One is that GRTS has two 6-byte RA (Receiver Address) fields, which contain the addresses of the two compatible receivers. Another difference is that GRTS includes two additional fields named *Rate* which are the feasible data transmission rates for the two receivers. The values of the *Rate* fields are calculated by the AP based on the channel state information. The rank of an RA in the RA list indicates the order in which the candidate receivers should respond CTS and ACK to the AP.

In the phase of data transmission, the AP sends data in different rates to the compatible receivers based on the independent channel states. The rate adaptation can be specified as

$$R_k[m] = \begin{cases} 0, & \text{if } SINR_k[m] < \beta_0 \text{ or } NAV_k[m] > 0; \\ R_i, & \text{if } \beta_i \le SINR_k[m] < \beta_{i+1}, \\ & k = 1, 2, \ldots, N-1; \\ R_N, & \text{otherwise.} \end{cases} \tag{21}$$

where R_k is the feasible data rate for user k, N 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 $11Mbps$, thus $N = 4$ under this scenario), R_i is the matched achievable data rate tailored to $SINR_k$, R_N is the highest feasible rate, and β_i and β_{i+1} are the lower and upper bound of the SINR to achieve a certain bit rate R_i. In our work, the values of different SINR thresholds for different data rates are chosen based on the settings of $Orinoco^{TM}$ 802.11b card (Orinoco PCMCIA Silver/Gold: $11Mbps \Rightarrow 16dB$; $5.5Mbps \Rightarrow 11dB$; $2Mbps \Rightarrow 7dB$; $1Mbps \Rightarrow 4dB$).

Packet bursting is an efficient approach to opportunistically exploiting high quality channels when it occurs via transmission of multiple back-to-back packets [4] [6]. Packet concatenation (PAC) [5] further eliminates many ACK and SIFS. As a result, the expected overhead per packet can be reduced and the channel utilization is potentially improved. In our work, we adopt the ideas that the maximum number of packets of a receiver in a transmission should be $\lfloor R_k/R_{base} \rfloor$ (R_{base} is the base rate of the system) in order to maintain the same temporal fairness characteristics as the single rate 802.11. It should be mentioned that the duration field in the data packet is set according to the maximum transmission time of the two compatible receivers which is essential for other nodes in the network to make Network Allocation Vector (NAV) settings accordingly.

B. Uplink Transmission

The dual uplink of MAD-UDD/TB can be similarly divided into two phases: scheduling and data transmission as shown in Fig. 5. Once a remote user m requests to send data to the AP, the AP will firstly send out a Multicast RTS (MRTS) (see Fig. 4(b)) which contains k RA fields to make polling on user m's k

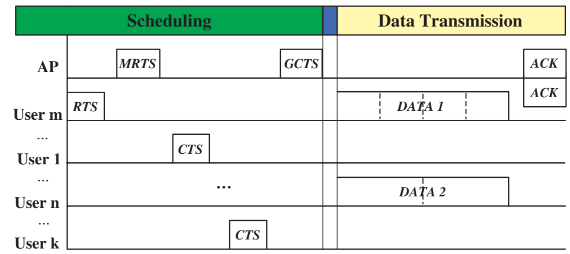

Fig. 5. The uplink of MAD-UDD/TB.

TABLE 1

COMPARISON AMONG 802.11B, OAR, MAD AND MAD-UDD/TB

Mechanism Title	802.11b	OAR	MAD	MAD-UDD/TB
Multi-rate Adaptation	-	√	√	√
Multiuser Diversity	-	-	√	√
Simultaneous Transmission	-	-	-	√

compatible peers to inquire whether they currently have backlogged packets. Based on the information in the replied CTSs and the complete knowledge of channel state information, the AP can decide who is the suitable compatible peer to user m complying with the scheduling policy of maximum uplink sum rate. Then the AP sends out Group CTS (GCTS) to notify the assigned compatible pair. GCTS (see Fig. 4(c)) is a control packet similar to the regular CTS but has two RA and rate fields to indicate the two compatible users and their matched rates for the following data transmission. The phase of data transmission is similar to that of the downlink. The two compatible users (m, n) respectively transmit $\lfloor R_k/R_{base} \rfloor (k = m, n)$ packets to the AP at the same time in the uplink. The AP can use the receiving filters $\mathbf{u}_m$ and $\mathbf{u}_n$ which are the transmission signatures for users m and n in the downlink to demodulate the data stream from the two users.

IV. SIMULATION RESULTS

In this section, we study the impact of MAD-UDD/TB on the expected network throughput in a wireless LAN with the AP equipped with two antennas and compare it with the single-rate 802.11b, OAR [6], and MAD [5]. The main difference of the four mechanisms is illustrated in Table 1 for brevity.

We consider a generic network where the AP is located at the center of a $300m \times 300m$ square area while each user is randomly distributed. The wireless LANs we investigated run in the Distributed Coordination Function (DCF) mode. The AP maintains a separate queue for each user and schedules in a round robin manner. Each node always has backlogged packets with packet length of 1500 bytes. The subset size of the candidate receivers and peers in downlink and uplink scheduling is 5 unless stated otherwise. The base rate is $2Mbps$ for all the multi-rate supported mechanisms. Free space and Rayleigh fading are used as the propagation model in all the experiments conducted. The maximum transmitting power for all nodes is $15dBm$ and the radio sensitivity for different data rates are configured according to $Orinoco^{TM}$ 802.11b card.

Four sets of simulation experiments have been carried out, in each of which one of the following four parameters varies: number of users N, side length of distribution area X, user mobile velocity V, and subset size of the candidates k.

a) Impact of Number of Users N: To study the multius-

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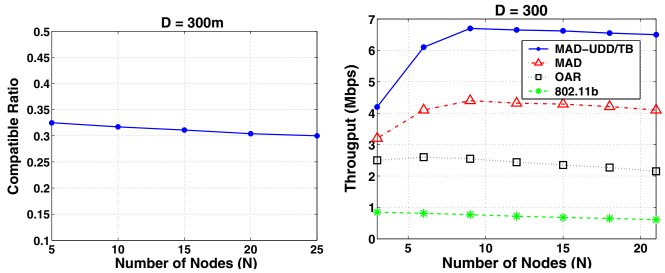

Fig. 6. (a) Compatible ratio vs. N; (b) Network throughput vs. N.

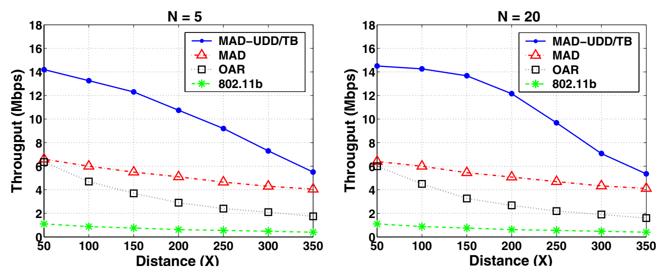

Fig. 7. Network Throughput vs. X (N = 5 and 20).

er gain, in this set of experiments, we vary the number of users N in the network, which indirectly also varies the number of traffic flows, as each flow is between a unique source-destination pair. Fig. 6(a) shows the variation of compatible ratio when N varies from 5 to 20. Compatible ratio is defined as $\eta = \frac{No.\ of\ compatible\ pairs}{No.\ of\ total\ pairs} = \frac{n}{1/2 \cdot N(N-1)}$. As can be seen from the figure, as the number of users increases, the compatible ratio maintains relatively stable, with only a small decrease. Fig. 6(b) plots the network throughput obtained with different MAC mechanisms when N varies from 3 to 21. As the number of users increases, the throughput gain of MAC-UDD/TB due to the opportunistic scheduling and simultaneous packet transmission is manifest and its performance maintains relatively stable when the number of users is more than 8.

b) Impact of Side Length X of Distribution Area: Fig. 7 compares the network throughput for 802.11b, OAR, MAD, and MAD-UDD/TB when X varies from $50m$ to $350m$ for N equals 5 and 20. The performance under these two scenarios is very similar and has only some discrepancy in values. It is evident that MAD-UDD/TB performs the best among all the mechanisms investigated. The benefits of multiuser diversity and simultaneous transmission are exploited to maintain the high data rate as the channel condition becomes worse while the performance of other schemes severely degrades. Compared to MAD, MAD-UDD/TB improves the network throughput by 35% to 120%. Compared to OAR, the improvement is 60% to 180%. 802.11b always performs the worst and is less than one ninth of that of MAD-UDD/TB.

c) Impact of User Mobility: In this set of experiments, we vary the velocity to evaluate the impact of user mobility on network throughput. The mobile velocity varies from $2m/s$ to $10m/s$ corresponding to the decrease of the channel coherence time. Fig. 8 shows that the network throughput of MAD-UDD/TB drops as the coherence time decreases. It is reasonable because the fluctuation of the channel condition greatly affects on users' compatibility and causes more packet retransmissions. This demands for more frequent update on the channel state

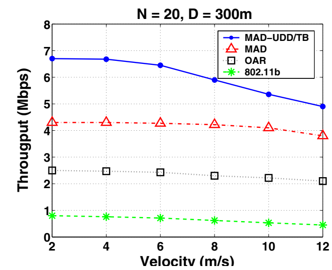

Fig. 8. Network Throughput vs. V.

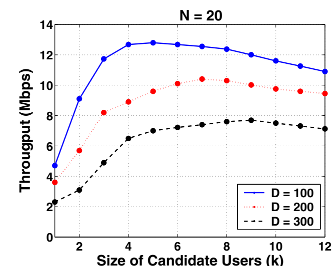

Fig. 9. Network Throughput vs. k.

information. As the channel is slow changing, the performance changes of all the mechanisms are small because that within this range of velocities, the coherence time is sufficiently long to extract the full performance gains.

d) Impact of Size of the Subset of Candidates k: We assume that both the subsets of candidates in the downlink and uplink scheduling have the same size k. Distance X varies from $100m$ to $300m$ to represent different cases in WLANs. The results are plotted in Fig. 9 from which we can draw some observations. First, the optimal value of k increases with the distance X. Secondly, the throughput improvement becomes less obvious when k is larger than 4, and the throughput decreases in all the cases when k is larger than 9. Larger k means more diversity, but the overhead in the control packets and especially the computing complexity introduced to the AP will sharply increase to overshadow the multiuser diversity gain.

V. Conclusions

In this paper, we propose a protocol named Medium Access Diversity with Uplink-Downlink Duality and Transmit Beamforming (MAD-UDD/TB). By utilizing the fact that the linear transmitting and receiving techniques in a multiple-antenna environment take into account the opportunistic scheduling among multiple users to prioritize transmissions, MAD-UDD/TB can support simultaneous transmissions both in the downlink and uplink, which further increases the effect of multiuser diversity. We formulate the problem of optimizing throughput as the scheduling to find a pair of compatible users with maximum sum rate among multiple candidate users. Extensive simulation results indicate that our protocol outperforms other medium access diversity and auto rate schemes with minimal additional overhead and minor modifications to the IEEE 802.11 standard.

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