Opportunistic MAC Protocol for Coordinating Simultaneous Transmissions in Multi-user MIMO based WLANs

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Abstract

Multi-user MIMO technology makes it possible for wireless nodes to successfully receive multiple packets from simultaneous transmitters in wireless networks. As it can provide more transmission opportunities without causing collisions, the network throughput performance can be dramatically improved. In this letter, we propose a medium access control (MAC) protocol, which allows more nodes to opportunistically transmit packets even though they do not exchange any control packets for transmission coordination if the AP can concurrently receive more packets due to the multi-packet reception capability. Through extensive simulations, we show that the proposed MAC protocol achieves significantly higher throughput performance in multi-user MIMO wireless networks.

Index Terms

MAC protocol, multi-user MIMO system, transmissions coordination.

I. INTRODUCTION

In conventional wireless local area networks (WLANs), nodes can receive only one packet at a time, while two or more concurrent transmissions cause all packet reception to fail: this is known as packet collision. However, as the technology level of multi-user multiple-input multiple-output (MIMO) and multi-user detection (MUD) increases, it has become possible for wireless nodes to successfully receive multiple packets from simultaneous transmitters. The mixed signal from

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simultaneous transmissions can be properly separated and decoded, and is preferred because it enhances the achievable throughput performance. The maximum number of packet transmissions that can be successfully decoded is defined as multi-packet reception (MPR) capability (denoted by M).

However, most traditional MACs have been designed without any consideration for MPR capability and do not function well in multi-user MIMO based WLANs. Consider an AP with MPR capability that can receive multiple packets simultaneously, but if the CSMA/CA based IEEE 802.11 DCF protocol is applied, the AP attempts to make only one successful transmission for each channel contention. For example, once a set of nodes transmits RTS packets first, all the other nodes are prohibited from sending data frames until all the on-going transmissions finish. As a result, the multi-user MIMO based wireless channel is under-utilized. Therefore, new types of MACs, which take multi-packet reception capabilities into consideration, are highly desired for multi-user MIMO WLANs. In this letter, we propose a MAC protocol, which allows nodes that have not won in channel contention to opportunistically transmit packets when the AP informs them it has vacant channel space for multiple packet reception.

II. SYSTEM MODEL AND MOTIVATION

We consider an uplink case for one-hop networks, where one access point (AP) is located at the center of the network and the other transmitters are located around the AP. We assume that the AP has M multiple antennas while each transmitter has one antenna. In this system, the mixed signal ($\mathbf{y}$) from N multiple transmitters can be expressed as

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{w}, \tag{1}$$

where $\mathbf{s} = [s_1,\ s_2,\ \cdots,\ s_N]^T$ and $\mathbf{y} = [y_1,\ y_2,\ \cdots,\ y_M]^T$ denote the transmitted and received signal vector, respectively. Also, $\mathbf{H}$ is the channel matrix and $\mathbf{w}$ is the channel noise. Here, the channel matrix $\mathbf{H}$ can be written as

$$\mathbf{H} = [h_1, h_2, \cdots, h_N], \tag{2}$$

where $h_i = (h_{1i}, h_{2i}, \cdots, h_{Mi})^T$ denotes the channel coefficient between i-th user and the AP with M antennas.

We consider a multiuser OFDM-based WLAN system as a practical MPR-capable system. Here, we assume that each frame includes an orthogonal training sequence in the preamble in order to make it possible for APs to estimate the channel coefficients as like IEEE 802.11n standard. Once an AP obtains the channel coefficients from the training sequences, it can properly decode the mixed signal from simultaneous transmitters and then simultaneously serve M users at a time. Note that each carrier in the multiuser OFDM system may have a different modulation so that each node can transmit at a different transmission rate [5].

In the MPR-capable networks, several MAC protocols have been proposed in order to improve the throughput performance in [1]–[4]. For example, Zhang [1] proposed the multi-round contention mechanism, with which an AP ***waits for*** a sufficient number of transmission requests from contending stations by giving them multiple contention chances in order to fully exploit packet reception capability. In [2], Zheng *et al.* proposed an adaptation mechanism to fully exploit the packet reception capability. In this protocol, each node is required to have exact knowledge about MPR capability and contending nodes ***before*** it sends the initial request control packet (i.e., RTS packet).

In this letter, we propose a MAC protocol, which permits another chance for stations that have not won in channel contention to simultaneously transmit packets at the same time when the intended transmitter is sending a data frame. In other words, nodes may have a second chance of sending data frames during a single transmission duration.

III. PROPOSED MEDIUM ACCESS CONTROL PROTOCOL

A. Overview

The detailed procedure of the proposed MAC protocol is as follows:

(S1) When nodes sense that the channel is idle, each node independently performs a back-off mechanism like the IEEE 802.11 DCF protocol. The node with the smallest back-off number transmits an RTS frame to the AP first. Note that the number of nodes sending RTS packets can be equal to or more than one. Let K denote the set of nodes sending RTS packets simultaneously. We also define k as the number of nodes sending RTS packets, i.e., $k = |K|$.

(S2) After the AP successfully receives the RTS frame, the AP identifies the number of vacant channel spaces, which is equal to $(M - k)$, and then broadcasts a CTS frame including the channel space information.

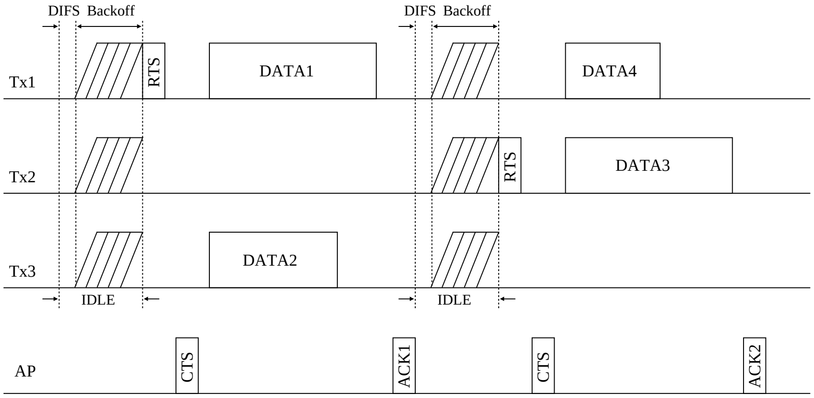

Fig. 1. Operation example of the proposed channel access protocol.

(S3) On receiving the CTS frame, a set of *winning nodes* that sent the RTS frame begins to send a data frame. At the same time, the other *candidate nodes* can transmit with a probability of p_t if their transmissions end no later than the longest transmission duration (denoted by τ_w) among K, i.e., $\tau_w = \max_{i \in K}(\tau_i)$ where τ_i is the transmission duration of *i*-th node.

(S4) Once the AP finishes receiving all the on-going transmissions, it immediately sends the ACK frame.

Figure 1 shows the example operation of the proposed protocol. In this example, M is set to two. In Figure 1, Tx1 is the first transmitter that has sent the RTS packet in the first transmission chance, and after receiving the CTS packet, Tx3 decides to transmit packets in the second transmission chance. Therefore Tx1 and Tx3 are transmitting data packets simultaneously during a single transmission duration.

As shown in the above example, our proposed channel access protocol improves the channel efficiency of multi-user MIMO WLANs. In the proposed protocol, if collision happens, the nodes retransmit the packet by using the same back-off mechanism as detailed in the IEEE 802.11 DCF. We emphasize here that after collisions occur, all the packets are lost.

B. Determining the transmission opportunity (p_t)

In the proposed protocol, in order to fully utilize the multi-packet reception capability (M) without causing packet collisions, we need to determine the appropriate level of transmission opportunity (p_t).

First, we assume that packet length is geometrically distributed with a mean of $1/q$. The geometrical distribution function is given by

$$P\{L \leq l\} = 1 - (1-q)^l, \tag{3}$$

where L is the random variable for packet length, l is the packet length, and the geometric distribution parameter q is assumed to be given in advance. Then, the distribution function of the transmission duration τ is expressed as $P\{t \leq \tau\} = P\{L \leq r_g \tau\} = 1 - (1-q)^{r_g \tau}$ where r_g is the transmission rate of the nodes belonging to a group $g \in \mathcal{G}$. Here, $\mathcal{G}$ is the set of available groups according to the transmission rates. Suppose that the winning node belongs to a group w. Then, the estimated number of candidate nodes that have shorter duration than τ_w in a group g (denoted by c_g^w) is obtained by

$$c_g^w = N_g(1 - (1-q)^{r_g \tau_w}), \tag{4}$$

where N_g is the number of candidate nodes belonging to group $g \in \mathcal{G}$ and is assumed to be readily available to the AP. Therefore, the total number of candidate nodes (c^w) is computed by $c^w = \sum_{g \in \mathcal{G}} c_g^w$.

We now consider the probability that j multiple transmissions exist among c^w candidate nodes in the second chance of transmissions. This probability follows a binomial distribution and is given by

$$P[X = j] = \binom{c^w}{j} p_t^j (1-p_t)^{c^w - j}, \quad j = 0, 1, \cdots, c^w \tag{5}$$

where X is a binomial random variable indicating the number of candidate nodes deciding to transmit with p_t.

Note that if more than $(M-k)$ candidate nodes access the channel simultaneously, then all the frames including k frames being transmitted by the winning nodes are collided. Taking the effect of these collisions into consideration, the expected payload (denoted by $M(p_t)$) for the second chance of transmissions is derived as follows:

$$M(p_t) = \sum_{j=0}^{M-k} P[X = j] \cdot (j \cdot \bar{l} + k \cdot \frac{1}{q}) \tag{6}$$

where $\bar{l}$ denotes the average packet size of candidate nodes. Suppose that the winning node belongs to the group w consisting of N_w nodes with the transmission rate of r_w. Then, $\bar{l}$ is obtained as follows:

$$\bar{l} = \sum_{w\in\mathcal{G}} \left(\frac{N_w}{N} \cdot \big(\sum_{g\in\mathcal{G}} \frac{c_g^w}{c^w} \cdot \bar{l}_g^w\big) \right), \tag{7}$$

where $\bar{l}_g^w$ is the average packet size of the candidate nodes belonging to the group g when the winning node belongs to the group w, and is given by

$$\bar{l}_g^w = \frac{\int_0^{\frac{r_g}{r_w}\cdot\frac{1}{q}} xq(1-q)^{x-1}\mathrm{d}x}{1-(1-q)^{\frac{r_g}{r_w}\cdot\frac{1}{q}}}. \tag{8}$$

In (6), the optimal transmission opportunity (denoted by $p_t^* = \mathrm{argmax}_{p_t\in[0,1]} M(p_t)$) that maximizes $M(p_t)$ can be numerically obtained.

As a practical solution, we can appropriately choose p_t such that the expected number of the candidate nodes deciding to transmit would be equal to the vacant channel space (i.e., $E[X] = M - k$). Note that $E[X]$ is given by $c^w \cdot p_t$ since X is a binomial random variable in (5). Then the transmission opportunity is expressed as

$$p_t = \begin{cases} \gamma(M-k)/c^w & \text{for } k < M \\ 0 & \text{otherwise,} \end{cases}$$

where γ is a tunable parameter. When γ is set to close to 1, the candidate nodes would aggressively transmit packets but may experience a number of transmission failures because it happens that the number of simultaneous transmissions is instantaneously larger than $(M-k)$. In contrast, as γ is set to a lower value, the channel would not be fully utilized. Note that there exists a tradeoff between channel utilization and collision occurrence. Therefore, γ should be carefully chosen, and in fact, it needs to be adjusted with respect to M and N.

Based on the computed value of p_t, the candidate nodes efficiently decide whether or not to transmit packets. Specifically, while the winning nodes begin to transmit data frames, the candidate nodes are allowed to transmit packets with a probability of p_t, which is specified in the CTS frame broadcast by the AP.

IV. NUMERICAL RESULTS

To evaluate the performance of our proposed protocol and compare it with that of the IEEE 802.11 DCF protocol and two other existing MPR protocols (Zhang's method [1] and Zheng's method [2]), we carry out various simulations using MATLAB. In the simulations, we assume that every node independently generates its data packet with a geometric distribution, and the

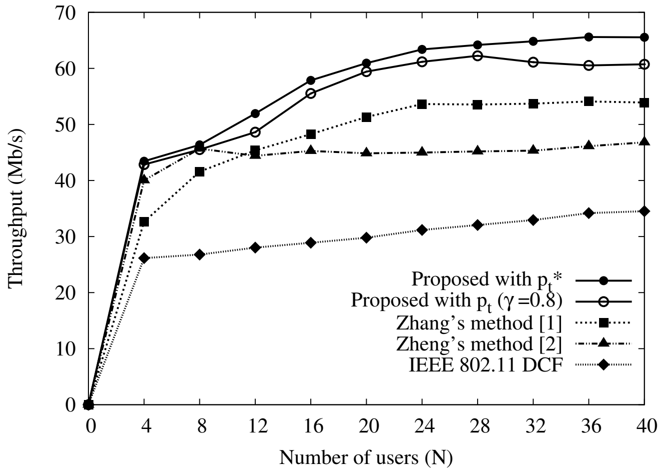

Fig. 2. Throughput performance w.r.t. the number of nodes.

average payload is 1500 bytes. Also, the wireless networks operate in the IEEE 802.11n mode that employs a MIMO-OFDM system. In this simulation, four different transmission rates are used for each group g: 15, 60, 120, and 150 Mb/s in IEEE 802.11n mode, and each group has the same number of nodes, i.e., N_g=$N/|\mathcal{G}|$. The tunable parameter γ is set to 0.8 in our simulations.

Figure 2 shows the simulation results of throughput performance with respect to the number of users (N). We vary N from 0 to 40 users, while M is fixed to 5. As shown in Figure 2, our proposed MAC protocol outperforms the other MPR protocols as well as IEEE 802.11 DCF. This is due to the fact that the candidate nodes may transmit packets to fully utilize the packet reception capability under the proposed protocol.

Figure 3 depicts the throughput performance with respect to the packet reception capability (M). In Figure 3, the throughput obtained by the IEEE 802.11 DCF mode is not improved although M increases. The reason is that the wireless channel fails to be fully utilized under the IEEE 802.11 DCF mode. However, the throughput obtained by our proposed method gradually increases as M increases. This implication is that the multi-user MIMO based wireless channel is more efficiently used by allowing more nodes to transmit packets in a single transmission duration.

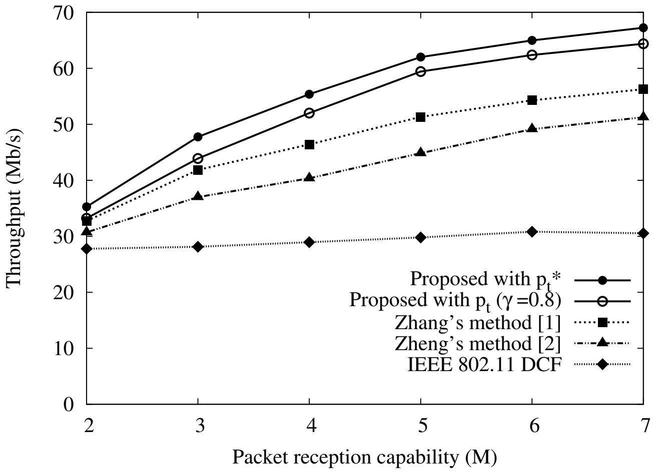

Fig. 3. Throughput performance w.r.t. the packet reception capability.

V. CONCLUSION

We studied the issues of improving the aggregate throughput of multi-user MIMO based WLAN systems. In particular, we focused on the fact that the wireless channel is under-utilized in the CSMA/CA based channel access protocol. To prevent this inefficient channel use, we proposed a MAC protocol for coordinating simultaneous transmissions, in which the candidate nodes can transmit packets on receiving the CTS packet although they have not sent RTS packets. Through various simulations, we showed that our proposed scheme significantly improves the throughput performance in multi-user MIMO based WLANs.

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