Mi-MMAC: MIMO-Based Multi-Channel MAC Protocol for WLAN

(Invited Paper)

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***Abstract*—In order to meet the proliferating demands in wireless local area networks (WLANs), the multi-channel media access control (MMAC) technology has attracted a considerable attention to exploit the increasingly scarce spectrum resources more efficiently. This paper proposes a novel multi-channel MAC to resolve the congestion on the control channel, named as Mi-MMAC, by multiplexing the control-radio and the data-radio as a multiple-input multiple-output (MIMO) array, working on both the control channel and the data channels alternately. Furthermore, we model Mi-MMAC as an M/M/k queueing system and obtain a closed-form approximate formula of the saturation throughput. Simulation results validate our model and analysis, and we demonstrate that the saturation throughput gain of the proposed protocol is close to 3.3 times compared with the dynamical channel assignment (DCA) protocol [1] under the few collisions condition.**

***Index Terms*—Media access control, Multiple-input multiple-output, Multi-channel, Wireless LAN.**

I. INTRODUCTION

Over the last few years, wireless local area networks (WLANs) have witnessed the rapid growth by the ease of installation and flexibility. With the ever-increasing mobile users and bandwidth demands of various applications, such as voice call, video conference, etc., the next generation wireless networks (i.e., IEEE 802.11ax [2]) has been paid close attention to utilize the limited spectrum resources efficiently, thereby improving the MAC efficiency.

Several multi-channel medium access control (MMAC) protocols have been proposed for WLAN to fully exploit the capabilities of available spectrum resources, by which multiple transmissions can concurrently take place on different frequency channels without interferences. Without requiring clock synchronization, the dedicated control channel based MMAC becomes popular in WLAN, which is represented by the dynamical channel assignment (DCA) protocol [1]. The basic idea of DCA is that each node is assumed to be equipped with two independent half-duplex radios, one of which, named as control-radio, tuning to the unique control channel permanently to contend for the chances of accessing data channels, while the other one is named as data-radio, dynamically switching to the selected data channel to transmit data packets. However, DCA protocol seriously suffers from the congestion on the control channel because that all of the data transmissions need to be granted by the handshakes on the dedicated control channel through a CSMA/CA mode. Therefore, this is a matter of great concern [3], [4].

We rethink DCA protocol that: the two radios of each node consistently work on the dedicated control channel and the selected data channel respectively. This leads to a high radio waste during the control messages exchanging (i.e., the data-radio is in a state of idle) as well as data transmission phase (i.e., the control-radio has almost been idle). In such situation, what if a joint design is considered by multiplexing the two radios as a multiple-input multiple-output (MIMO) array?

In this paper, we propose a novel MMAC, named as Mi-MMAC, to multiplex the control-radio and the data-radio as a 2x2 MIMO array, working on both the control channel and the data channels alternately. By running two transmitters and receivers on the same channel, spatial multiplexing gain can be achieved. This greatly enhances the utilization of radios, doubles the transmission efficiency of the MAC protocol data units (MPDUs), and finally relieves the congestion on the dedicated control channel significantly.

The main contributions of this paper can be summarized as follows:

- To the best of our knowledge, we are the first to study the control channel congestion problem based on MIMO transmission technology.
- We present an analytical model and then obtain a closed-form approximate formula of the saturation throughput. In addition, we derive the upper bound of saturation throughput gain under the few collisions condition.
- By deploying extensive simulations, we demonstrate that the saturation throughput gain of our proposed protocol is approximate 3.3 times of traditional DCA protocol.

The remainder of the paper is organized as follows. In Section II, Mi-MMAC is proposed which details how the protocol works. The analytical model and the performance analysis are shown in Section III, followed by the validation with extensive simulations in Section IV. Section V concludes the paper.

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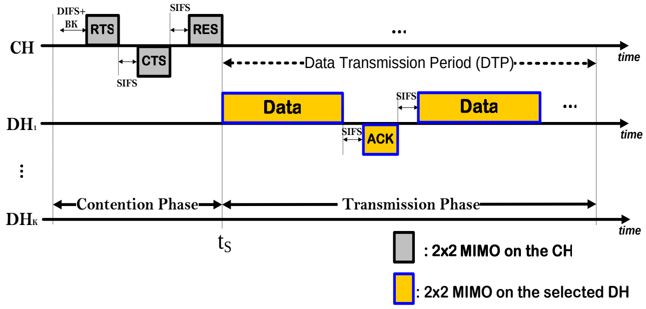

Fig. 1. The proposed Mi-MMAC protocol.

II. THE PROPOSED MIMO-BASED MULTI-CHANNEL MAC PROTOCOL

A. System Frame

We consider a static wireless network consisting of N contending nodes and $K+1$ orthogonal frequency channels, one of which is the control channel (CH), and correspondingly, the others are configured as data channels, denoting the ith data channel by $DH_i, i = 1, ..., K$. Each node in the network is equipped with two independent half-duplex radios, without interfering with each other. In this paper, we do not distinguish these two radios since they are assumed to work jointly as a MIMO array all the time.

The operation of Mi-MMAC is illustrated in Fig. 1, which contains two phases:

- **Contention Phase.** By multiplexing the idle data-radio on the control channel, the sender competes to exchange the control packets by following the rule of IEEE 802.11 DCF with 2x2 MIMO, which is denoted as $\mathrm{MIMO}_{\mathrm{CH}}$.
- **Transmission Phase.** After the successful handshake on the control channel, the communication pair simultaneously switches their radios to the selected data channel and transmits data packets with 2x2 MIMO.

B. Contention Phase

Assume that the sending node S, has data packets to send to the destination node D, it then firstly contends to access to the control channel by IEEE 802.11 DCF. If succeed, by the way of 2x2 MIMO, sends an request-to-send (RTS) packet, including the information of data transmission period (DTP) and its available channel list ($\mathrm{ACL}_{\mathrm{S}}$), which indicates the data channels that both are virtual carrier sensing idle and physical carrier sensing idle, to avoid the hidden terminals. Once receiving the RTS packet, node D selects one of the common available data channels, for example, DH_1 illustrated in Fig. 1, and then replies a clear-to-send (CTS) packet. Finally, S broadcasts a reservation (RES) packet on the control channel to announce the selected data channel and the corresponding DTP information. Moreover, by using of 2x2 MIMO, the data rate of the control MPDUs (i.e., RTS, CTS and RES packets) is improved, which halves the total durations.

C. Transmission Phase

After the control messages exchanging successfully, the communication nodes simultaneously switch their radios to the selected data channel at the moment of t_S. Similar to the operations on the control channel, 2x2 MIMO transmission on the selected data channel is constructed by multiplexing their idle control-radios, which doubles the transmission rate of Data and ACK packets, and the number of data transmission initiated during the DTP is increased accordingly. As soon as finishing the data transmission, the communication nodes switch their two radios back to the control channel again to keep monitoring until having new packets to send or receive.

To sum up, there are two characteristics of Mi-MMAC:

- By employing the data-radio multiplexing, the control channel access efficiency is improved, which significantly relieves the congestion on the dedicated control channel.
- By multiplexing the control-radio on the selected data channel, data transmission can be increased during a DTP, which doubles the system throughput steadily.

III. PERFORMANCE ANALYSIS

In this section, we present the analytical model and then derive the saturation throughput gain of the proposed protocol.

A. Analytical Model

We model the proposed protocol as an M/M/k queueing system [5] to analyze the performance of the proposed Mi-MMAC. The rate of a node getting access to the data channel is consider as the arriving rate of the queueing model, which can be obtained as λ. And the departure rate of the queueing model is obtained as $\mu_i = i\mu$, $1 \leq i \leq K$ when i data channels are being used, where each data channel is released with the rate $\mu = 1/\mathrm{E}_{\mathrm{S}}$ and E_{S} denotes the average time of successful transmission on the data channel. According to the Bianchi's model [6], the average time successfully transmitted in a slot time on the control channel is $P_S P_{tr}$, and thus the arrival rate λ can be expressed as:

$$\lambda = \frac{P_S P_{tr}}{(1-P_{tr})\sigma + P_{tr}P_S T_S + P_{tr}(1-P_S)T_C}, \tag{1}$$

where P_{tr} is the probability that there is at least one transmission in a slot time, and P_S is the probability that a successful transmission occurs. $T_S = DIFS + RTS + CTS + RES + 3H_{PHY} + 2SIFS$ denotes the average time the control channel is sensed busy caused by a successful transmission, $T_C = DIFS + RTS + H_{PHY}$ indicates the average time that the control channel suffers a collision, H_{PHY} is the physical header, σ means the duration of an empty slot time.

Let π_i denote the steady probability when there are i data channels being used in the system. By using $\sum_{i=0}^{K} \pi_i = 1$, we can obtain:

$$\pi_i = \frac{\rho^i / i!}{\sum\limits_{j=0}^{K} \rho^j / j!}, i = 0, 1, ..., K, \tag{2}$$

where $\rho = \lambda/\mu$. Finally, the throughput can be computed as:

$$\mathbb{S} = \sum_{i=1}^{K} \pi_i \times i \times \mathrm{B} \times \frac{\mathrm{E_P}}{\mathrm{E_S}}, \tag{3}$$

where B denotes the bandwidth of a data channel, and $\mathrm{E_P}$ is the average time to transmit a data packet payload. According to (2) and the Taylor's formula, we have:

$$\sum_{i=1}^{K} \pi_i \times i = \rho \cdot \frac{e^{\rho} - \mathrm{R}_{K-1}(\rho)}{e^{\rho} - \mathrm{R}_{K}(\rho)}, \tag{4}$$

when K is appropriately large, the Taylor remainders $\mathrm{R}_K(\rho)$ and $\mathrm{R}_{K-1}(\rho)$ can be neglected from the theoretical point of view, which leads to $\sum_{i=1}^{K} \pi_i \times i \approx \rho$. Substituting the approximation into (3), the saturation throughput $\mathbb{S}$ can be further approximated as:

$$\mathbb{S} \approx \lambda \times \mathrm{B} \times \mathrm{E_P}. \tag{5}$$

B. Saturation Throughput Gain

Notation: The parameters below with subscript "D" represent the DCA protocol (e.g., $Para_{\mathrm{D}}$) and the parameters with subscript "M" denote that our proposed Mi-MMAC is being used (e.g., $Para_{\mathrm{M}}$).

Denote $\mathbb{F}$ as the saturation throughput gain factor of Mi-MMAC compared with DCA.

Theorem 1. $\mathbb{F}$ is proportional to the minimum number of transceiver antennas, and its upper bound exists as follows:

$$\mathbb{F} \overset{\sim}{\leq} \min(n_T, n_R) \cdot \theta, \tag{6}$$

where the symbol "$\overset{\sim}{\leq}$" means that it is an approximated upper bound, θ is defined as $\theta \triangleq T_{S\_\mathrm{D}}/T_{S\_\mathrm{M}}$. In addition, $T_{S\_\mathrm{D}} = T_S$ and $T_{S\_\mathrm{M}} \approx DIFS + (RTS + CTS + RES)/\min(n_T, n_R) + 3H_{PHY} + 2SIFS$.

Proof: It is evident that a reasonable assumption is that $\sigma << T_C$, which leads to $\frac{(1-P_{tr})\sigma}{P_{tr}P_S T_S + P_{tr}(1-P_S)T_C} \leq \frac{(1-P_{tr})\sigma}{P_{tr}T_C} \to 0$ with a relatively large number of sending nodes. Thus it can be concluded from (1) that $\lambda \approx 1/(T_S + (1 - P_S)T_C/P_S)$. Meanwhile, according to (5), it is clear that:

$$\mathbb{F} = \frac{\mathbb{S}_{\mathrm{M}}}{\mathbb{S}_{\mathrm{D}}} = \frac{\lambda_{\mathrm{M}}}{\lambda_{\mathrm{D}}} \frac{\mathrm{B_M}}{\mathrm{B_D}} \frac{\mathrm{E_{P\_M}}}{\mathrm{E_{P\_D}}}, \tag{7}$$

where $\mathrm{B_M} = \min(n_T, n_R) \cdot \mathrm{B_D}$, $\mathrm{E_{P\_M}} = \frac{Num \cdot \mathrm{E_{P\_D}}}{\min(n_T, n_R)}$, n_T and n_R represent the number of transmitting antennas and receiving antennas respectively. Num denotes the number of data transmission can be initiated during a DTP, which is doubled by 2x2 MIMO, thus we have $\mathrm{E_{P\_M}} = \mathrm{E_{P\_D}}$. In addition, considering the inequality $T_{C\_\mathrm{D}} T_{S\_\mathrm{M}} \leq T_{C\_\mathrm{M}} T_{S\_\mathrm{D}}$ always holds in our proposed protocol, which leads to:

$$\frac{\lambda_{\mathrm{M}}}{\lambda_{\mathrm{D}}} \approx \frac{T_{S\_\mathrm{D}} + (1 - P_S)T_{C\_\mathrm{D}}/P_S}{T_{S\_\mathrm{M}} + (1 - P_S)T_{C\_\mathrm{M}}/P_S} \leq \frac{T_{S\_\mathrm{D}}}{T_{S\_\mathrm{M}}}, \tag{8}$$

where $P_S \leq 1$. After algebraic simplifications and approximations, we can finally obtain from (7):

$$\mathbb{F} \overset{\sim}{\leq} \frac{T_{S\_\mathrm{D}}}{T_{S\_\mathrm{M}}} \cdot \min(n_T, n_R) = \min(n_T, n_R) \cdot \theta. \tag{9}$$

This completes the proof. ■

The aforementioned analysis suggests that, the MIMO transmission on the data channel brings a relatively fixed gain, $\min(n_T, n_R)$. By using a appropriately large K, the gain brought by MIMO on the control channel is totally embodied with the $\lambda_{\mathrm{M}}/\lambda_{\mathrm{D}}$ when DTP is fairly small (i.e., there is only one data packet can be transmitted during a DTP without using MIMO transmission on the data channel), and the upper bound can be obtained nearly as θ. Moreover, considering the 2x2 MIMO transmission scheme used in our proposed protocol, we can obtain from (9) that:

$$\mathbb{F} \overset{\sim}{\leq} \min(n_T, n_R) \cdot \theta = 2\theta\ . \tag{10}$$

IV. PERFORMANCE EVALUATION

In this section, the performance of Mi-MMAC is evaluated by extensive simulations using ns-2 simulator (ns-2.33), in terms of the aggregate throughput and average packet delay.

In our simulations, we deploy a single-hop wireless LAN scenario and the migration delay of antennas is ignored. Moreover, the bandwidth of the control channel is 2 Mbps, data channels are equal in bandwidth with 11 Mbps. All channels are assumed to be ideal, in the sense that there is no errors occurred. The number of contending nodes is 10, DTP equals to 1 ms, packet payload size is 1024 bytes. Other parameters are set as follows: SIFS = 10 μs, DIFS = 50 μs, $\mathrm{CW_{min}}$ = 15 slots and the back-off slot time equals to 20 μs. Compared with DCA protocol, the theoretical saturation throughput gain factor of the proposed protocol is calculated according (10) as $\mathbb{F} \overset{\sim}{\leq} 2\theta = 3.3$.

Fig. 2 shows the theoretically analyzed and simulated aggregate throughput of DCA and Mi-MMAC. It can be seen that the analytical and simulation results are well matched, especially when the number of data channels is appropriately

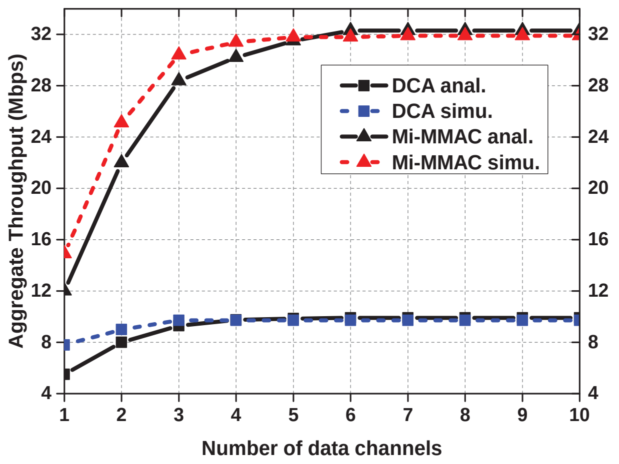

Fig. 2. Aggregate throughput versus number of data channels.

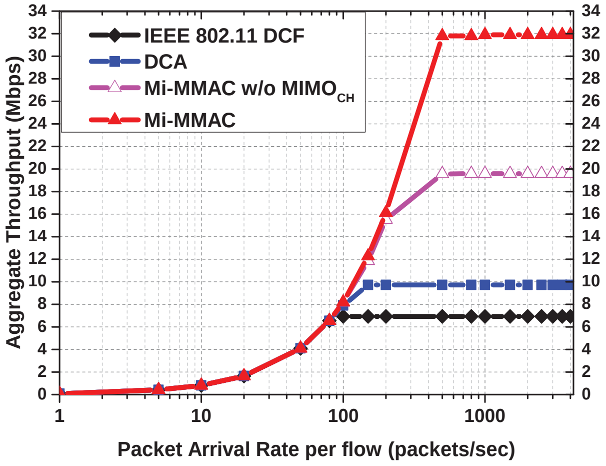

Fig. 3. Aggregate throughput versus packet arrival rate per flow.

large, which validate our theoretical analysis model. Moreover, the congestion on the control channel is significantly alleviated with 2x2 MIMO transmission scheme, thus more channel resources can be exploited efficiently in Mi-MMAC, which leads to a considerably improvement of the system throughput.

Fig. 3 illustrates the aggregate throughput as the packet arrival rate increases while the average packet delay is shown in Fig. 4. We consider that there are 11 channels, including one control channel and 10 data channels. It can be observed from these two figures that as the network traffic load draws near saturation, Mi-MMAC dramatically outperforms IEEE 802.11 DCF and DCA. Moreover, a relatively stable twice spatial multiplexing gain can be obtained by just using 2x2 MIMO transmission on the data channel, which is evidenced by the simulation results illustrated in Fig. 3, i.e., $\mathbb{S}^{'}_{\mathrm{M}}/\mathbb{S}_{\mathrm{D}} \approx 2.01$, where $\mathbb{S}^{'}_{\mathrm{M}}$ denotes the saturation throughput of Mi-MIMO without MIMO$_{\mathrm{CH}}$. Moreover, when applying 2x2 MIMO transmission on the control channel additionally, compared with DCA, we can observe that the saturation throughput of Mi-MMAC is further improved as $\mathbb{S}_{\mathrm{M}}/\mathbb{S}_{\mathrm{D}} \approx 3.25$, which is close to the approximated analytical upper bound (i.e., $\mathbb{F}\overset{\sim}{\leq}2\theta = 3.3$), particularly in the networks with few collisions. Furthermore, the average packet delay is decreased notably by means of 2x2 MIMO in our proposed protocol, which can be validated by the simulation results in Fig. 4.

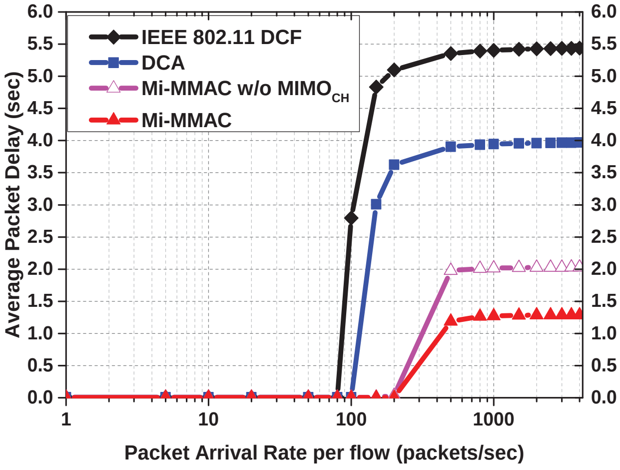

Fig. 4. Aggregate throughput versus packet arrival rate per flow.

V. CONCLUSION

The congestion problem on the dedicated control channel is a significant challenge in multi-channel MAC protocol design. In this paper, we study this issue by multiplexing the control-radio and the data-radio as a MIMO array, working on both the control channel and the data channels alternatively. In addition, an M/M/k queueing model is presented to evaluate the system performance of the proposed protocol. Simulation results have been provided to validate our analysis and to demonstrate that the saturation throughput gain is nearly up to 3.3 times of traditional DCA protocol under the few collisions condition.

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