An Efficient Downlink MAC Protocol for Multi-User MIMO WLANs

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Abstract

Multi-User Multiple-Input Multiple-Output (MU-MIMO) technology has recently attracted significant attention from academia and industry because of it is increasingly important role in improving networks' capacity and data rate. Moreover, MU-MIMO systems for the Fifth Generation (5G) have already been researched. High Quality of Service (QoS) and efficient operations at the Medium Access Control (MAC) layer have become key requirements. In this paper, we propose a downlink MU-MIMO MAC protocol based on adaptive Channel State Information (CSI) feedback (called MMM-A) for Wireless Local Area Networks (WLANs). A modified CSMA/CA mechanism using new frame formats is adopted in the proposed protocol. Specifically, the CSI is exchanged between stations (STAs) in an adaptive way, and a packet selection strategy which can guarantee a fairer QoS for scenarios with differentiated traffic is also included in the MMM-A protocol. We then derive the expressions of the throughput and access delay, and analyze the performance of the protocol. It is easy to find that the MMM-A protocol outperforms the commonly used protocols in terms of the saturated throughput and access delay through simulation and analysis results.

Keywords: MU-MIMO, MAC, adaptive CSI feedback, differentiated traffic, QoS

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1. Introduction

Nowadays the demands for data rate and wireless networks' capacity in Wireless Local Area Networks (WLANs) are becoming increasingly high, which is drawing considerable attention to researchers for ubiquitous challenges. To meet the demands of people, Multiple-Input Multiple-Output (MIMO) technology is proposed to improve the performance of WLANs [1]. However, Single-User MIMO (SU-MIMO) where two devices with multiple antennas communicate with each other is far from meeting the requirements of human beings. In order to further increase the data transmission rate, Multi-User MIMO (MU-MIMO) technology is put forward in IEEE 802.11ac [2] which provided an up to 866.7 Mbps data rate per data stream. MU-MIMO systems are generally less sensitive to the propagation environment than SU-MIMO. Moreover, MU-MIMO can greatly improve spectral efficiency [3]. Recently, the 5G technology introducing massive MIMO which introduces antenna arrays with a few hundred antennas has made great progress [4-5]. Specifically, massive MU-MIMO systems using irregular antenna arrays raise public attention [6]. Massive MU-MIMO systems can enhance the capacity without additional bandwidth [7]. In the downlink transmission, Access Point (AP) with multiple antennas is able to communicate with different stations (STAs) at the same time by MU-MIMO systems and the multiplexing gain can be shared by all STAs. As a result, MU-MIMO technology has been widely applied around the world.

To fully utilize the MU-MIMO capability for performance enhancement in WLANs, it is essential to understand the fundamental impact of MU-MIMO on the MAC layer design. More and more downlink MU-MIMO MAC protocols are proposed in the open literatures. The downlink transmission schemes in these protocols enable the simultaneous communication based on the Channel State Information (CSI) required at the transmitter or receiver. The CSI characterizes the combined effect of wireless channel on a signal. In the context of downlink MU-MIMO, the CSI at the AP makes it possible to cancel the multi-user interference. Practically, the perfect CSI cannot be acquired from the complicated characteristics of wireless channel, and the fresh CSI is needed at the AP to conduct the Multi-User Interference Cancellation (MUIC). On the other hand, the frequent CSI feedback introduces redundancy overheads to the network while the out-dated CSI may lead to the failure of MUIC. Thus, an adaptive CSI feedback mechanism is of great importance in a downlink MU-MIMO MAC protocol.

Generally, QoS is an important performance indication in WLANs. IEEE 802.11e first provided QoS for WLANs by the Enhanced Distributed Channel Access (EDCA) and Hybrid Controlled Channel Access (HCCA) mechanism. Instead of going through all the aspects of IEEE 802.11e, we only refer to the EDCA part that is tightly close to our protocol. EDCA divides the packets from upper layer with different priorities into four Access Categories (ACs), each AC independently contends for the channel access with specific EDCA parameters such as Contention Window (CW) and Arbitrary Inter-Frame

Space (AIFS). The EDCA mechanism is proved to work well in WLANs with differentiated traffic [8-9], but a problem that the traffic with high priority may be aggressive in some cases arises when the traffic load is heavy.

In this paper, a downlink MU-MIMO MAC protocol with adaptive CSI feedback is proposed, which can support differentiated traffic at the same time. Unlike most of the MAC protocols in which the CSI is fed back to the AP in every transmission attempt, the proposed protocol only invokes the CSI feedback process when the CSI is somewhat out-dated. The receiver, i.e. STA, can roughly estimate the channel conditions in an explicit way by recording the successful ratio of packet delivery within a specific period. Moreover, our protocol treats the differentiated traffic in a fairer way than IEEE 802.11e EDCA mechanism. A simple but practical algorithm including frame aggregation for choosing packets from the AC queues is presented. Simulation results and theoretical analysis show that the downlink MU-MIMO MAC protocol based on adaptive CSI feedback outperforms the commonly used protocols in terms of the throughput, access delay and MAC queue status.

The remainder of this paper is organized as follows. Section 2 introduces related work. In Section 3, the proposed protocol is thoroughly characterized, including system model, a modified access method, a packet selection strategy and operational processes. The theoretical analysis is given in Section 4. In Section 5, analysis and simulation results are shown to evaluate the performance of the MMM-A protocol. Section 6 presents concluding remarks and future works in this field.

2. Related Work

To make the best of the capability of physical layer featured with MIMO, corresponding adaptations at the MAC layer are needed. Therefore, a number of MAC protocols are proposed in the open literatures. In [10], Mirkovic et al. proposed a MAC protocol based on IEEE 802.11 standard where the CSI was obtained at the receiver side. They introduced three new control frames – M-RTS, M-CTS and M-ACK to integrate MIMO into IEEE 802.11 WLANs. Moreover, the protocol gave a flexible and scalable support to multiple antenna terminals. However, it is only applied in the single-user scenario. The authors of [11] proposed two cross-layer schemes, namely U-MAC and D-MAC, which jointly selected the MIMO coding scheme at the physical layer and the minimum contention window size at the MAC layer to maximize the network utility for the IEEE 802.11e MAC. However, the SU-MIMO cannot make full use of spatial multiplexing so that it becomes a major obstacle to achieve higher data transmission rate. In [12], an analytical model was presented to analyze the saturation throughput and average access delay of the CSMA/CA-based MAC protocol for MU-MIMO WLANs, which considered a simple distributed opportunistic transmission scheme that allowed the clients to contend for the concurrent transmission opportunities under certain conditions. However, the developed model only focuses on the uplink transmission. In [13], a novel uplink MU-MIMO MAC protocol was presented to reduce the overheads in the uplink transmission. The frame exchange sequence of the MAC protocol was proved to be efficient by computer simulations. Different from our work, STAs transmitted access requests to the AP in an OFDMA manner and the pilots were transmitted in a TDMA manner in the uplink MU-MIMO MAC protocol.

In [14], Shrestha et al. presented a MAC layer design which was supported by the precoding vectors obtained by zero forcing technique to solve the Hidden Terminal (HT) problem. Moreover, the proposed MAC protocol adopted an efficient channel sounding method to obtain the CSI from the clients. However, the design has a higher signaling overhead compared to RTS/CTS scheme. Authors of [15] designed an experimental downlink MU-MIMO system considering resolution of CSI quantizer and CSI feedback channel data rates to implement the downlink transmission in an elaborate way. Operations of physical layer were considered in the system while that of MAC layer were not mentioned. Moreover, the CSI feedback channel in the system was realized over a cable which cannot be used in practice. A distributed MU-MIMO MAC protocol was proposed in [16]. The protocol can be applied to the scenario that users had either one or multiple antenna elements. The authors investigated the maximum number of users that can be supported in a stable network by theoretical analysis. It was notable that the CSI feedback was so frequent that it introduced overheads. And the staggered CTS frame and ACK frame decreased the time utility of the proposed MAC protocol. Liao et al. [17] proposed a unified MU-MIMO MAC protocol to support both MU-MIMO downlink and uplink transmissions. The protocol adopted the implicit CSI feedback, namely, the AP estimates the channel using the training sequence. More details of MU-MIMO MAC protocols were referred in [18].

The QoS provided in IEEE 802.11e has drawn more and more attention to networking researchers. Weihua Helen Xi et al. evaluated the effectiveness of QoS for different types in IEEE 802.11e WLANs in [19]. They claimed that the QoS of IEEE 802.11e was an effective improvement to support low delay services at a cost of decreasing quality of low priority traffic and analysed that the interframe spaces and contentions window sizes had an impact on the performance of different traffic types. The inborn retransmission problem that decreased the channel efficiency was also demonstrated. Through simulations the authors found that EDCA [20-21] had better ability to handle real time applications with high QoS requirements than the legacy IEEE 802.11 DCF. However, EDCA cannot provide QoS guarantee when heavily loaded traffic exists, which is different from our work that a novel packet selection strategy can guarantee a fairer QoS. The authors of [22] explained the reason why Transmit Opportunity (TXOP) did not support downlink MU-MIMO transmission. Because the existing rules in EDCA cannot allow the simultaneous transmission of multiple frames belonging to different ACs, which limited the application of the downlink MU-MIMO technology. Hence, it proposed a TXOP Sharing mechanism, which had been included in the IEEE 802.11ac. The main modification of TXOP in EDCA was the addition of TXOP Sharing between the initiation of the TXOP and the multiple frames transmission within a TXOP. If an Access Category (AC) became the owner of a TXOP, it decided whether to share the TXOP with other ACs for simultaneous transmissions. If it did, the aforementioned TXOP became a Multi-User

TXOP (MU-TXOP). But when another AC had the same destination as the owner of the current TXOP, it cannot share the current TXOP. A Markov chain-based model considering the integration of TXOP sharing mode was presented in [23] to analyze the performance of the TXOP sharing mechanism in IEEE 802.11ac. It was proved that the TXOP sharing mechanism can make use of the bandwidth efficiently and achieve better fairness among different types of traffic.

Compared with the above work, this paper presents a scheme which the CSI is fed back to AP in an adaptive way and a fairer packet selection strategy for scenarios with differentiated traffic. After our verification, it greatly improves the performance of WLANs.

3. The Downlink MMM-A Protocol

As we all know, the frequent CSI feedback increases redundancy overheads. Therefore, we design the downlink MMM-A protocol which the CSI is exchanged in an adaptive way by a key indication, the successful ratio of packet delivery. In the downlink MMM-A protocol, only when the CSI is outdated, is the CSI feedback process invoked. Moreover, the MMM-A protocol includes a packet selection strategy which guarantees fairness in heavy traffic load situations.

3.1 System Model

In our design, we consider the scenario where AP is equipped with M antennas, while each STA just has one antenna. The number of the antennas equipped on an AP is smaller than the number of STAs. AP can simultaneously communicate with multiple STAs by multiple antennas and STAs just can transmit or receive a packet at one time. Moreover, STAs can only communicate with AP, and there is no direct communication among STAs. The system model is shown in the **Fig. 1.**

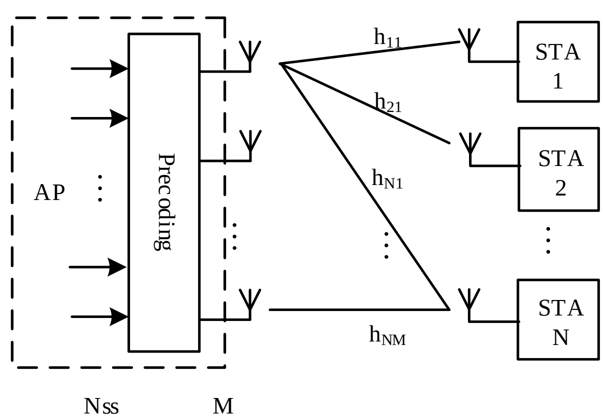


Fig. 1. System model

Assume that there are N STAs and one AP in the network. Since an AP with M antennas can only communicate with M STAs, MU-MIMO requires selecting M STAs. Our focus is on the downlink data transmission while the uplink transmission can inherit the traditional DCF scheme in IEEE 802.11. The number of spatial streams is N_{ss} . That is, there are N_{ss} data symbols being transmitted simultaneously in a transmission round. The data symbols which are denoted as $\mathbf{x}$ should be processed by a precoder before transmitted. In our downlink scheme, the precoder can be represented as a precoding matrix $\mathbf{P}$. Considering an AP with M antennas and a set of selected STAs, the channel matrix can be written as

$$\mathbf{H} = [\mathbf{H}_1{}^T \quad \mathbf{H}_2{}^T \quad \cdots \quad \mathbf{H}_M{}^T]^T \tag{1}$$

where $\mathbf{H}_i = [h_{i1} \quad h_{i2} \quad \cdots \quad h_{iM}]$ is the channel matrix from the AP to the *i-th* STA. The received signal of STAs can be written as

$$\mathbf{y} = \mathbf{HPx} + \mathbf{n} \tag{2}$$

where $\mathbf{n}$ is a Gaussian noise vector added to the data signal. Taking a zero forcing precoder into account, the precoding matrix can be calculated at the AP by

$$\mathbf{P} = \mathbf{H}^H (\mathbf{H}\mathbf{H}^H)^{-1} \tag{3}$$

With the zero forcing precoder, the interference among data symbols intended for the specific STA can be canceled. The CSI, including the SNR and channel matrix, is acquired at the STAs through training process and then fed back to the AP.

3.2 Extension of the RTS/CTS Channel Access Method

The proposed MAC protocol extends the RTS/CTS access method of IEEE 802.11 DCF to support the downlink MU-MIMO. As it says in section 3.1, AP can send different packets to different STAs with different antennas at the same time. The number of the simultaneous transmission is not bigger than that of the AP’s antennas. To reserve the channel with multi-station for AP, we modify the frame format of RTS, making it have receiver address fields. There is a new field named update in RTS frame to indicate whether the CSI should be refreshed. The value of the update field depends on the successful rate which is a statistical indication maintained by the MAC entity. More exhaustive operations will be introduced in section 3.4. Furthermore, a CSI filed is contained in CTS frame for AP to get the channel matrix which is necessary in precoding process. **Fig. 2** shows the new frame format of RTS, while **Fig. 3** illustrates the new frame format of CTS.

The CSI can be calculated at the STA side using the training sequence included in the physical header of a frame. Several training protocols at the MAC Layer are proposed to support downlink MU-MIMO transmission in [24]. Based on a custom downlink MU-MIMO MAC protocol, the training process can be implemented in implicit/explicit, polled/scheduled way. It is claimed that the training overhead of explicit feedback cannot be ignored when the number of antennas becomes large. Here a High Throughput (HT) PPDU format defined in IEEE 802.11ah is adopted at the physical layer. Several training fields are contained in physical header. The training sequence which is known by both the transmitter and receiver is used to estimate the channel.

Frame Control	Duration	RA1	•••	RAM	TA	Update	FCS

Fig. 2. The new format of RTS frame for MU-MIMO

Frame Control	Duration	RA	TA	CSI (Optional)	FCS

Fig. 3. The new format of CTS frame for MU-MIMO

A common downlink transmission procedure adopted by many MU-MIMO MAC protocols is shown in **Fig. 4**. The scheme has been extended to MU-MIMO scenario based on CSMA/CA channel access method. We assume that there are adequate data frames in the queue of AP. The AP first transmits RTS frame to reserve the channel when it wins the contention with STAs. STAs included in the receive fields of RTS will calculate the downlink CSI with the training sequence in RTS and then responds to the AP by sending CTS frame in which the CSI is contained in a scheduled way. As long as the AP receives all the CTS frames from the destined STAs, it gets the CSI and then deduces the downlink channel matrix. Then precoding is conducted at the AP using the deduced channel matrix. Multiple data frames are transmitted to the STAs simultaneously after precoding procedure. Finally, the intended STAs will send the ACK frame to the AP upon receiving the data frames. In this transmission scheme, the CSI is calculated and fed back to the AP in every round. These operations cancel out the interferences among parallel data frames and guarantee the accuracy of communication. However, the overheads introduced by the frequent exchange of CSI are notable, which decrease the efficiency of channel utilization. Furthermore, STAs transmit the CTS frames in a staggered way, which ignores the capability of multiple packets reception of AP.

In order to fully use the frequency and time resource, an adaptive CSI feedback downlink MU-MIMO MAC protocol is proposed in this paper. It is an extension of the aforementioned transmission scheme. The AP maintains the successful rate of data transmission $R_{success}$ and threshold $Thr_{success}$. If $R_{success}$ is smaller than $Thr_{success}$, it indicates that the CSI need refreshing and the update field of RTS will be set to UPDATE_Y by AP. The transmission procedure described in **Fig. 4** will be invoked. If $R_{success}$ is larger than $Thr_{success}$, the CSI is fresh enough and the update field of RTS will be set to UPDATE_N by

AP. The downlink transmission will be different from that under common conditions. Since the AP has acquired fresh downlink CSI, it can receive multiple CTS frames simultaneously from the STAs without CSI in CTS. Moreover, it does not need deducing the channel matrix and precoding matrix. In this way, time is greatly saved and the channel utilization is higher than that of common transmission. The rest operations are the same as that characterized in **Fig. 4**.

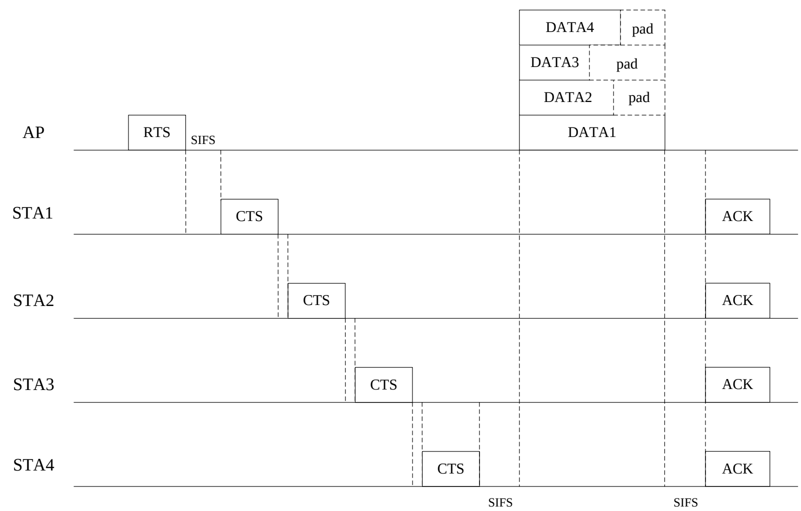


Fig. 4. A common downlink MU MIMO transmission

3.3 Packets Selection Strategy

Since there are multiple packets being transmitted simultaneously in the downlink, the strategy of packet selection is of great importance to achieve high network performance and fairness among different types of traffic. The objective of the packet selection strategy is to prepare proper packets for the coming transmission round. Each STA is equipped with a single antenna so that only one packet can be received at the same time. Therefore, the destinations of selected packets should be different. Furthermore, the guarantee of QoS requires elaborate allocation to different types of traffic. Similar to IEEE 802.11e, the upper traffic with eight user priorities (UPs) are divided into four access categories (ACs): voice (AC_VO), video (AC_VI), best effort (AC_BE) and background (AC_BK). Different ACs have different priorities, hence, the selection strategy should make sure that the four ACs are treated differently according to their priorities.

Assume that the AP is equipped with M antennas, the proposed packet selection strategy is as follows:

1: Find the partition of M using an integer partition algorithm. That is, write M as a sum of positive integers. If $M = 4$, the partitioned results are: {4}, {3, 1}, {2, 2}, {2, 1, 1} and {1, 1, 1, 1}. The number of partitions of M is denoted as L which can be calculated by the partition function $p(M)$, i.e.

$$L = p(M) \tag{4}$$

In the example above, the number of partitions of 4 is 5. Each partition represents a way of allocation of transmitting antennas at the AP side. For example, {2, 1, 1} may tell the AP to send AC_VO packets through 2 antennas, AC_VI packets through 1 antenna and AC_BE packets through the rest 1 antenna.

2: Allocate the transmitting antennas for different ACs. According to the QoS requirements of different ACs, the weights of four ACs are denoted as p_1, p_2, p_3 and p_4. That is, the number of transmitting packets belonging to each AC should match the weights within a long enough period of time. Considering $M = 4$, the possible results of allocation is shown in **Table 1**.

3:

Table 1. Allocation results for $M = 4$

Mode	Allocation Results				Corresponding Partition
	Antenna 1	Antenna 2	Antenna 3	Antenna 4	
1	AC_VO	AC_VO	AC_VO	AC_VO	{4}
2	AC_VO	AC_VO	AC_VO	AC_VI	{3, 1}
3	AC_VI	AC_VI	AC_BE	AC_BE	{2, 2}
4	AC_VI	AC_VI	AC_BE	AC_BK	{2, 1, 1}
5	AC_VO	AC_VI	AC_BE	AC_BK	{1, 1, 1, 1}

4: Select a mode randomly and then search for the corresponding packets from Select a mode randomly and then search for the corresponding packets from the AC queues based on that mode. Note that the destination of the selected packets should be different from each other. This selecting process is illustrated in **Fig. 5**.

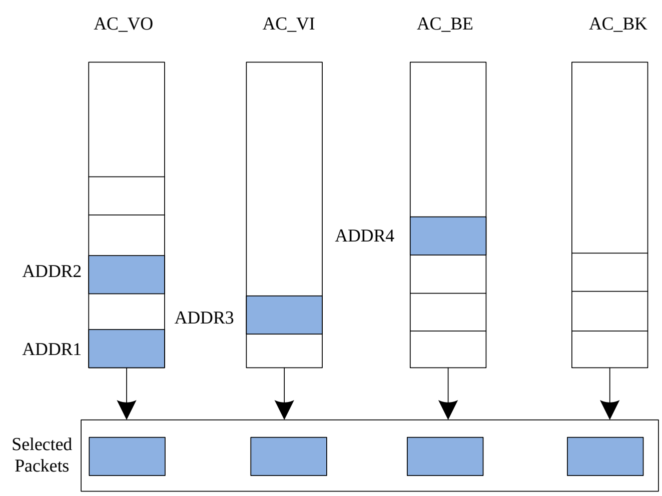


Fig. 5. Packets selection

Adopting our packets strategy, packets belonging to different ACs are transmitted according to their weights which can be even configured flexibly. Thus the provided QoS and network throughput are well balanced.

3.4 Operations of the Downlink MMM-A Protocol

Considering the extended channel access method and the proposed packets strategy, we can give the specific operations of the proposed protocol. The detailed operational procedure of the downlink MMM-A protocol is described by the pseudo code **Algorithm 1.**

Algorithm 1 Operations of the downlink MMM-A protocol

Initialize $R_{success}$ and $Thr_{success}$
while There are data packets in the queue of AP **do**
  Select packets from the queue
  Fill the RA fields of RTS frame according to the destinations
  Check the value of $R_{success}$
  if $R_{success} < Thr_{success}$ **then**
    Set the update field of RTS to UPDATE_Y
  else
    Set the update field of RTS to UPDATE_N
  end if
  AP initiates random backoff specified in IEEE 802.11 DCF
  AP sends a RTS frame to reserve the channel
  After STAs receive the RTS, STAs check the update field
  if The update field is UPDATE_Y **then**
    CTS frames which don't include the CSI are transmitted to AP simultaneously
  else
    CTS frames which include the CSI are transmitted to AP respectively
  end if
  AP sends multiple data packets at the same time
  STAs simultaneously respond with ACK frames upon receiving the data packets
  AP updates the $R_{success}$
end while

4. Theoretical Analysis

In this section, based on the Markov chains model for the backoff window size, we analyze the saturation throughput and access delay of our proposed protocol which applies to the RTS/CTS access mechanism under an ideal condition. For simplicity, we have made the following assumptions. 1) The data packet loss due to the time varying channel and the hidden/exposed terminal problem are ignored; 2) The probability of channel estimation in a transmission round is approximately known by simulation; 3) The probability of data packet collision is constant.

4.1 Saturation Throughput Analysis

Suppose there are n nodes in the network, including one AP and $n-1$ STAs. Since the proposed protocol is an extension of CSMA/CA in IEEE 802.11 DCF, our analysis is based on the work of [25]. In [25], Bianchi et al. analyze the performance of IEEE 802.11 DCF. They derive the following relationship between the collision probability p and transmission probability τ in a generic slot. The equation is

$$\begin{cases} p = 1-(1-\tau)^{n-1} \\ \tau = \dfrac{2(1-2p)}{(1-2p)(W+1)+pW(1-(2p)^m)} \end{cases} \tag{5}$$

In (5), W denotes the value of minimum contention window and m represents the number of backoff stages. Therefore the value of contention window of stage i, which is denoted as W_i, can be written as $W_i = 2^i W$. Equation (5) can be solved by a numeric technique.

We now go further based on the already known p and τ. The probability that there is at least one node willing to transmit packet is

$$P_{tr} = 1-(1-\tau)^n \tag{6}$$

The probability that there is only one transmission in a generic slot is

$$P_S = n\tau(1-\tau)^{n-1} \tag{7}$$

From the AP's point of view, the probability of a successful transmission is

$$P_{S\_AP} = \tau(1-\tau)^{n-1} \tag{8}$$

Since there are $n-1$ stations in the network, the probability that they experience a successful transmission is

$$P_{S\_STA} = (n-1)\tau(1-\tau)^{n-2}(1-\tau) = (n-1)\tau(1-\tau)^{n-1} \tag{9}$$

From the description of the proposed downlink MU-MIMO MAC protocol, we note that there are three types of events happening in a generic slot. The generic slot mentioned here is a general concept. It means not only the slot time specified in IEEE 802.11, but also the transmission or collision time between two slot times. The most obvious one is the slot is idle and the backoff timer of all the nodes will decrease by one. This slot does not contribute to the network throughput. Another condition that must be taken into account is the packet collision happening in a slot. A successful transmission in a slot which contributes to the throughput is also an important event.

For the first event above, the time interval T_i can be represented as

$$T_i = \sigma \tag{10}$$

where σ is the basic time unit needed to detect the transmission of a packet specified in IEEE 802.11. In condition where a collision happens, all the nodes in the network have to wait for T_{DIFS} after the collision as shown in **Fig. 6(a)**. The time interval T_C in this case has the expression

$$T_C = T_{RTS} + T_{DIFS} \tag{11}$$

where T_{RTS} means the RTS transmission time and T_{DIFS} means the DCF Interframe Space. There are three types of successful transmission in our protocol. They are shown in **Fig. 6(b)**, **Fig. 6(c)** and **Fig. 6(d)**. In the transmission round where the CSI is needed for the AP, the CTS frame including the CSI has to be transmitted one by one as shown in **Fig. 6(b)**. The time interval T_{S1} can be written as

$$T_{S1} = T_{RTS} + 3 \cdot T_{SIFS} + M \cdot T_{CTS} + T_{DATA} + T_{ACK} + (M-1) \cdot T_{CIFS} + T_{DIFS} \tag{12}$$

where T_{SIFS} is the Shortest Interframe Space, T_{CTS} means the CTS transmission time, T_{DATA} means the data transmission time, T_{ACK} means the ACK transmission time, T_{CIFS} means the Interframe Space between CTS frames, and *M* means the number of antennas at the AP. For the situation where there is no need to estimate the channel at the AP, the time interval T_{S2} can be obtained by

$$T_{S2} = T_{RTS} + 3 \cdot T_{SIFS} + T_{CTS} + T_{DATA} + T_{ACK} + T_{DIFS} \tag{13}$$

If one of the stations wins the contention, the time interval of a successful transmission T_{S3} is given by

$$T_{S3} = T_{S2} = T_{RTS} + 3 \cdot T_{SIFS} + T_{CTS} + T_{DATA} + T_{ACK} + T_{DIFS} \tag{14}$$

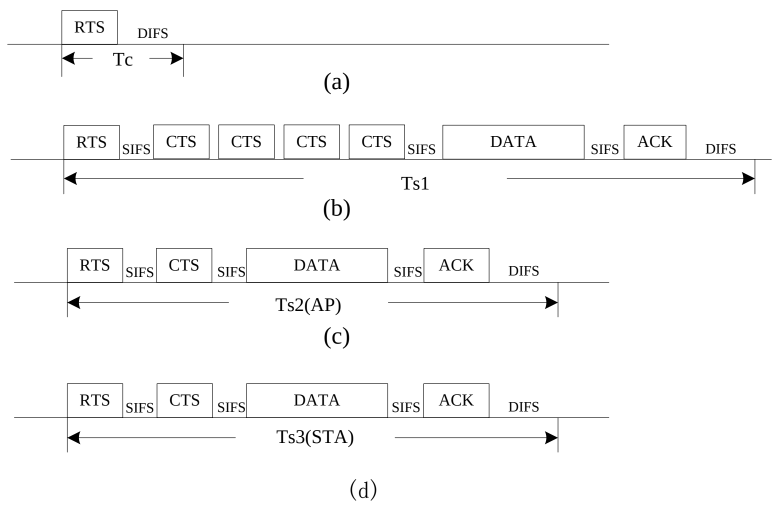


Fig. 6. Time intervals in the proposed protocol

Now let us consider the probability that the above time intervals appear in the timeline. It is apparent that the probability that the slot is idle is $1-P_{tr}$. The probability that a collision happens in a slot is $P_{tr}-P_S$. For a successful transmission round of the AP, the probability of the two types of transmission are $P_{S\_AP}\cdot P_{CSI}$ and $P_{S\_AP}\cdot(1-P_{CSI})$, where P_{CSI} means the probability of channel estimation in a transmission round. For a successful transmission round of a station, the probability is P_{S_STA}. Therefore, the average slot interval in our protocol is

$$E[Slot]=(1-P_{tr})\sigma+(P_{tr}-P_S)T_C+P_{S\_AP}\cdot((1-P_{CSI})T_{S2}+P_{CSI}T_{S1})+P_{S\_STA}T_{S3} \quad (15)$$

The total throughput in a generic slot $E[Data]$ can be obtained by

$$E[Data]=P_{S\_AP}\cdot M\cdot E[P]+P_{S\_STA}\cdot E[P] \quad (16)$$

where $E[P]$ means the average packet length in bits.

Finally the saturation throughput S is given by

$$S=\frac{E[Data]}{E[Slot]} \quad (17)$$

4.2 Expressions of the Average Access Delay

Here only the access delay of packets sent by AP is considered. [26] analyzes the access delay of the tranditional DCF. We will first conclude the work of [26] and then give our results. Suppose all the processes a packet will go through before a successful transmission. For a comprehensive analysis, the retransmission of a packet has to be considered. The access delay D can be represented as

$$D = A + T \tag{18}$$

where T is the transmission time of a packet, and A denotes all the backoff intervals, collision durations and the successful transmission time not involving the considered node. With a certain number of retransmissions, the packet will go through several backoff intervals, their associated interruptions and a collision interval for each retransmission. A can be written as

$$A^{(i)} = \sum_{j=0}^{i} B_i^{(j)} + \sum_{j=1}^{i} C_{ij} \tag{19}$$

where i is the number of retransmission, B is backoff intervals and their interruptions for each retransmission, C is the collision intervals of the considered node for each retransmission. We can decompose B into two parts so that it can be represented as

$$B = \sum_{k=1}^{BO_j} (\sigma + I_k) \tag{20}$$

where σ is the basic time unit specified in IEEE 802.11, and BO_j is the value of backoff timer for the specific retransmission number j, I is the interruptions that the backoff timer may go through in a slot. [26] derives the expression of I

$$I = \begin{cases} 0 & w.p. \quad 1-p \\ \overline{T} & w.p. \quad q \\ \overline{C} & w.p. \quad p-q \end{cases} \tag{21}$$

where p is collision probability in a generic slot, q is the probability that there is only one transmission among the rest $n-1$ nodes, $\overline{T}$ denotes the successful transmission time of any of the rest $n-1$ nodes, $\overline{C}$ denotes the collision intervals not involving the considered node. More details can be found in [26].

Following the arguments above, we will analyze the access delay of packets in our proposed protocol. Since the CSMA/CA mechanism of DCF is adapted, the backoff method is the same as the DCF and the similar analysis method above can be used. The only differences are the transmission and collisions intervals. From the AP's point of view, the interruptions to its backoff timer are due to the transmissions and collisions of the other stations as shown in (21). According to the proposed protocol, $\overline{T}$ and $\overline{C}$ can be obtained by

$$\overline{T} = T_{RTS} + 3 \cdot T_{SIFS} + T_{CTS} + T_{DATA} + T_{ACK} + T_{DIFS} \tag{22}$$

$$\overline{C} = T_{RTS} + T_{SIFS} + T_{CTS} + T_{DIFS} \tag{23}$$

For the AP itself, the successful transmission interval T can be given by

$$T = T_{DIFS} + T_{DATA} + T_{RTS} + P_{CSI}(M \cdot T_{CTS} + (M-1) \cdot T_{CIFS}) + (1 - P_{CSI})T_{CTS} + 2T_{SIFS} \tag{24}$$

And the collision interval involving the AP C can be denoted as

$$C = T_{DIFS} + T_{RTS} + T_{SIFS} + P_{CSI}(M \cdot T_{CTS} + (M-1) \cdot T_{CIFS}) + (1 - P_{CSI})T_{CTS} \tag{25}$$

5. Numerical Results

In this section, analysis and simulation results are presented in order to evaluate the performance of the MMM-A protocol. A fully connected network with one AP and several STAs is considered. A simulator developed by MATLAB is used to conduct this simulation. Three typical protocols of MU-MIMO MAC are included in our simulations. They are MMM-N, MMM-E and MMM-A, which represent MU-MIMO MAC protocol without CSI feedback, with CSI feedback every attempt and with adaptive CSI feedback. We first study the saturated throughput of each protocol against the number of nodes. The downlink throughput of the proposed protocol is also discussed. The performance of the adaptive MU-MIMO MAC protocol under variable channel states is also considered. Then we compare the average access delay under different the number of nodes. At last, we focus on the length of MAC queue of the above three protocols, and prove the advancement of MMM-A protocol.

The MAC parameters are listed in **Table 2** [26].

Table 2. MAC Parameters Used in Numerical Results

Parameter	**Value**
Payload size	8000bits
PHY header	192bits
MAC header	272bits
ACK	PHY header+112bits
Time slot	20µs
SIFS	10µs
CIFS(CTS Interframe space)	5us
Basic Rate	1Mbps
Data Rate	2Mbps
The number of antenna M	4
RTS (including 4 receiver)	PHY header +304bits
CTS(without CSI)	PHY header+112bits
CTS(with CSI)	PHY header+1984bits
CW_{min}	31
CW_{max}	1023

5.1 Saturated Throughput

This simulation are conducted under saturated conditions. The average arrival rate of each STA and AP is 50 kbps and 500kbps respectively.

Fig. 7 shows the comparison of our analytical and the simulation results and it is obvious that they are nearly matched with each other. Four scenarios with different MAC protocols and parameters are included in the figure. It contains the above three protocols, namely, MMM-N, MMM-E and MMM-A. We can see that MMM-N, which assumes that perfect CSI is known and there is no need to feedback the CSI, has the highest throughput. With CSI feedback in every transmission round, MMM-E is not that efficient and only reaches a throughput of up to 1Mbps. We test our proposed protocol in two scenarios with different channel conditions. Channel 1 is a flat fading channel while channel 2 is a fast fading one. The proposed protocol, MMM-A, reaches a higher throughput under channel 1 than that under channel 2. It is because that in a flat fading channel, the proposed protocol need not to update the CSI frequently. Thus the overload is smaller than that of a fast fading channel.

Fig. 8 gives the relationship between the number of nodes and the saturated throughput of AP. It expresses the similar result which is shown in **Fig. 7**. Another point is that the throughput of AP is decreased as the number of nodes increases. The explanation is there are more STAs contending to access to the channel and correspondingly the AP gets less chance to transmit.

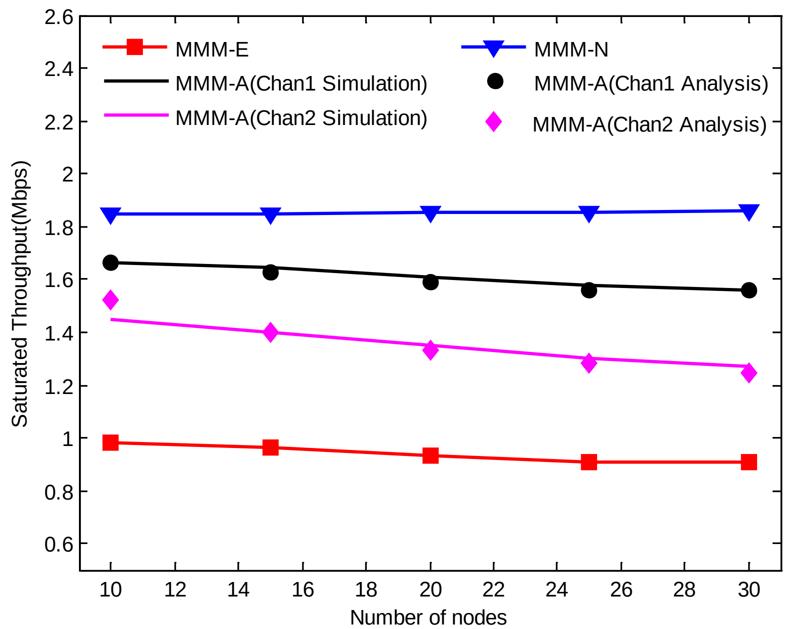


Fig. 7. Total saturated throughput

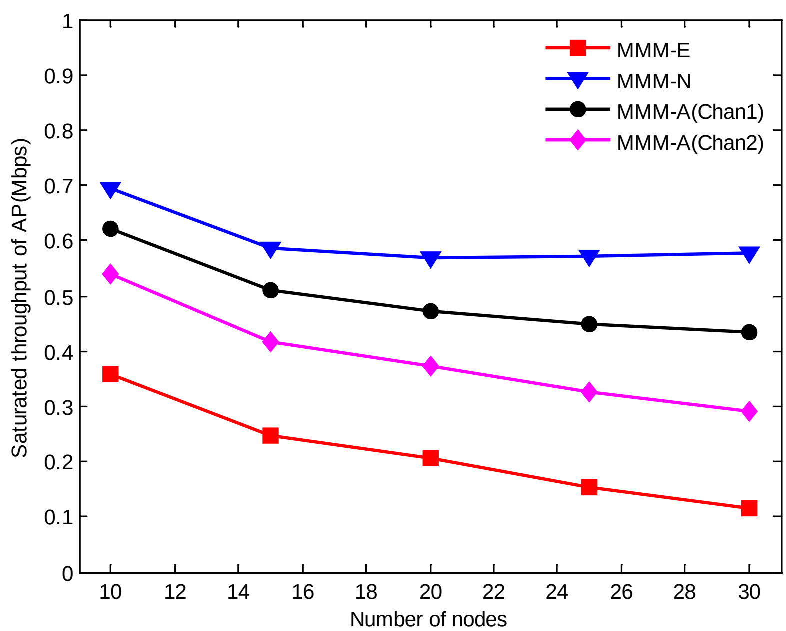


Fig. 8. Saturated throughput of AP

5.2 Average Access Delay

The access delay represents the timeliness of the protocol. It is defined as the time interval between the instant that a node begins to reserve the media when sending a packet and the instant that the packet is correctly received. **Fig. 9** shows not only the relationship between the number of nodes and the access delay above the three protocols but also the comparison of analytical and simulation results obtaining in the MMM-A protocol. The figure indicates that: 1) theoretical analysis of the average access delay is correct; 2) as the number of node increases, the access delay of all the three protocols increases. The ideal protocol, MMM-N, has the smallest delay while the MMM-E has the biggest latency because of the frequent CSI exchange. The dynamic and more practical one, MMM-A, keeps an acceptable delay.

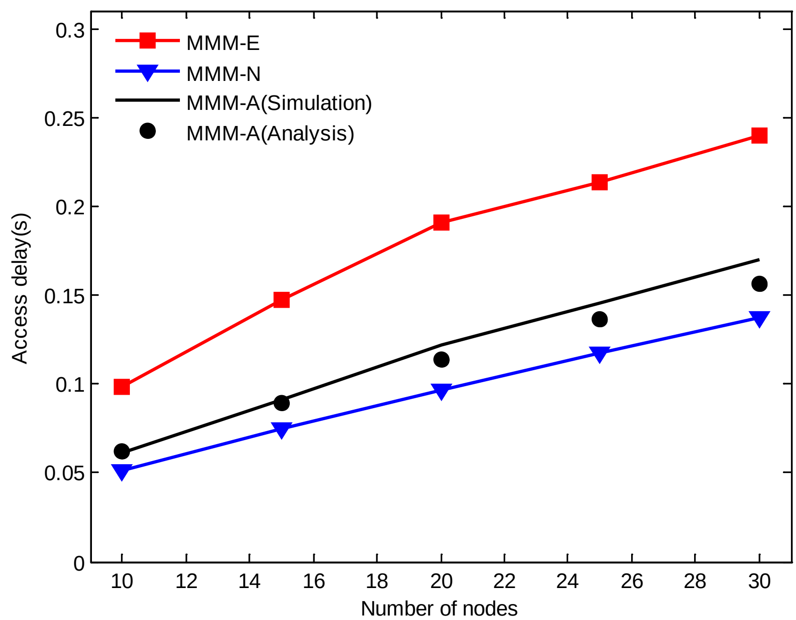


Fig. 9. Average access delay

5.3 Length of MAC Queue

The length of MAC queue is defined as the number of packets waiting for transmission. It decides the average delay of every packet. The queue status in the simulation is presented in **Fig. 10**. The accumulate average length of the queue is an effective indicator of queue status. If there is no CSI feedback in the protocol, such as MMM-N, the packet in the queue will not wait for much time to be transmitted and the length of queue is at a relatively low level. For a protocol that CSI is needed in every transmission round, such as MMM-E, there will be more packets waiting in the queue and the length is longer than MMM-N. The proposed MMM-A protocol has the number of packets in the queue between MMM-E and MMM-N.

It is useful to check the queue status. As the traffic load and the channel condition change, the proposed MMM-A protocol can change the queue buffer correspondingly, thus the utilization efficiency is improved.

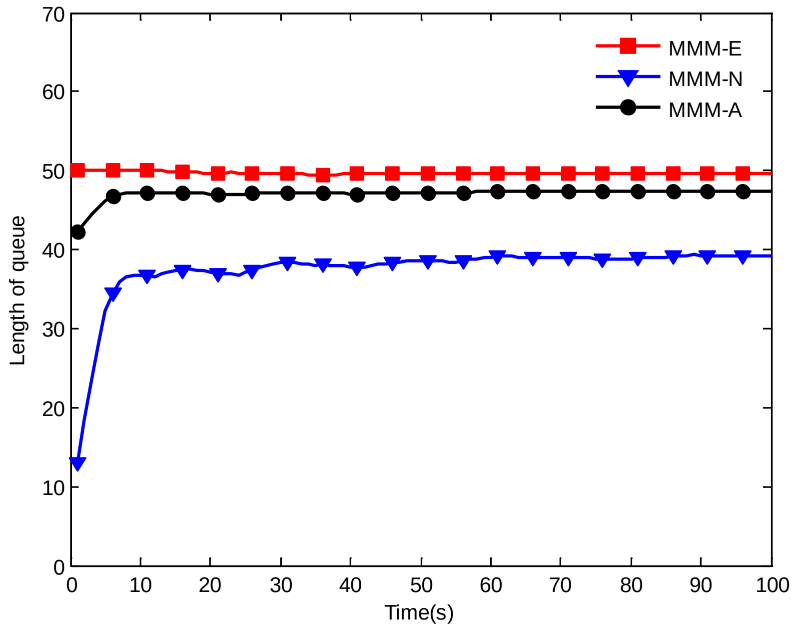


Fig. 10. Accumulate average length of MAC queue vs. simulation time

6. Conclusion and Future Work

In this paper, a novel downlink MU-MIMO MAC protocol is proposed to make full use of the MU-MIMO technology. We modify the format of RTS frame to make AP be able to simultaneously reserve the channel with multiple nodes. A packet selection strategy is also designed to handle differentiated traffic. The highlight of the proposed protocol is the adaptive CSI feedback mechanism, which improves the channel utilization by avoiding unnecessary CSI exchange. According to analysis and simulation results, we can find that the total saturated throughput of the MMM-A protocol increases by about 60% compared with the MMM-E protocol and the average access delay of the MMM-A protocol reduces by approximately 42% than that of the MMM-E protocol. It proves that the MMM-A protocol could greatly improve the network performance in terms of both the throughput and access delay.

Considering the channel condition at the MAC layer, our protocol can operate more effectively using a key indicator, the successful ratio of packet delivery. The future work will focus on studying what the optimized value of the indicator is and solving the quantization of fairness of the packet selection strategy. We will also assess the viability of our protocol regardless of the environment and compare our proposed work with other similar work under current network conditions.

References

[1] Y. J. Choi, N. H. Lee, and S. Bahk, "IEEE 802.11 performance enhancement by MIMO spatial multiplexing," in *Proc. of IEEE 16th International Symposium on Personal, Indoor and Mobile Radio Communications*, pp. 87-91, September 11-14, 2005. Article (CrossRef Link)

[2] "IEEE standard for information technology telecommunications and information exchange between systems-local and metropolitan area networks-specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. amendment 4: Enhancements for Very High Throughput for Operation in Bands below 6 GHz," *IEEE Std. 802.11ac*, 2013. Article (CrossRef Link)

[3] D. Finn, H. Ahmadi, A. Cattoni, and L. Da Silva, "Improved Spectral Efficiency through Multi-User MIMO across Small Cells," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 9, pp. 7764-7768, November, 2015. Article (CrossRef Link)

[4] P. Patcharamaneepakorn, S. Wu, C. -X. Wang, H. Aggoune, M. Alwakeel, X. Ge, and M. Di Renzo, "Spectral, Energy and Economic Efficiency of 5G Multi-cell Massive MIMO Systems with Generalized Spatial Modulation," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 12, pp. 9715-9731, February, 2016. Article (CrossRef Link)

[5] D. Araújo, T. Maksymyuk, A. Almeida, T. Maciel, J. Mota, and M. Jo, "Massive MIMO: survey and future research topics," *IET Communications*, vol. 10, no. 15, pp. 1938-1936, October, 2016. Article (CrossRef Link)

[6] X. Ge, R. Zi, H. Wang, J. Zhang, and M. Jo, "Multi-user massive MIMO communication systems based on irregular antenna arrays," *IEEE Transactions on Wireless Communications*, vol. 15, no. 8, pp. 5287-5301, August, 2016. Article (CrossRef Link)

[7] L. Lu, G. Y. Li, A. L. Swindlehurst, A. Ashikhmin, and R. Zhang, "An overview of massive MIMO: Benefits and challenges," *IEEE Journal of Selected Topics in Signal Processing*, vol. 8, no. 5, pp. 742-758, October, 2014. Article (CrossRef Link)

[8] C. Huang and W. Liao, "Throughput and delay performance of IEEE 802.11e enhanced distributed channel access (EDCA) under saturation condition," *IEEE Transactions on Wireless Communications*, vol. 6, no. 1, pp. 136-145, January, 2007. Article (CrossRef Link)

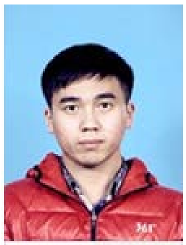
[9] M. Yazid, N. Sahki, and L. Bouallouche-Medjkoune, "Modeling and performance study of the packet fragmentation in an IEEE 802.11e-EDCA network over fading channel," *Multimedia Tools & Applications*, vol. 74, no. 21, pp. 9507-9527, November, 2015. Article (CrossRef Link)

[10] J. Mirkovic, G. Orfanos, H. J. Reumerman, and D. Denteneer, "A MAC protocol for MIMO based IEEE 802.11 wireless local area networks," in *Proc. of IEEE Wireless Communications and Networking Conference*, pp. 2131-2136, March, 2007. Article (CrossRef Link)

[11] Y. Lin and V. W. Wong, "Cross-layer design of MIMO-enabled WLANs with network utility maximization," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 5, pp. 2443-2456, May, 2009. Article (CrossRef Link)

[12] S. Wu, W. Mao, and X. Wang, "Performance study on a CSMA/CA based MAC protocol for multi-user MIMO wireless LANs," *IEEE Transactions on Wireless Communications*, vol. 13, no. 6, pp. 3153-3166, June, 2014. Article (CrossRef Link)

[13] T. Tandai, H. Mori, K. Toshimitsu, and T. Kobayashi, "An efficient uplink multiuser MIMO protocol in IEEE 802.11 WLANs," in *Proc. of IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, pp. 1153-1157, September 13-16, 2009. Article (CrossRef Link)
[14] S. Shrestha, G. Fang, E. Dutkiewicz, and X. Huang, "Zeroforcing precoding based MAC design to address hidden terminals in MU-MIMO WLANs," in *Proc. of IEEE 22nd International Conference on Telecommunications*, pp. 283-288, April 27-29, 2015. Article (CrossRef Link)
[15] D. Samardzija, H. Huang, R. Valenzuela, and T. Sizer, "An experimental downlink multiuser MIMO system with distributed and coherently coordinated transmit antennas," in *Proc. of IEEE International Conference on Communications*, pp. 5365-5370, June 24-28, 2007. Article (CrossRef Link)
[16] L. X. Cai, H. Shan, W. Zhuang, and X. Shen, "A Distributed Multi-User MIMO MAC Protocol for Wireless Local Area Networks," in *Proc. of IEEE Global Telecommunications Conference*, pp. 1-5, November 30-Dcecmber 4, 2009. Article (CrossRef Link)
[17] R. Liao, B. Bellalta, T. M. Cao, J. Barcelo, and M. Oliver, "Uni-MUMAC: a unified down/up-link MU-MIMO MAC protocol for IEEE 802.11ac WLANs," *Wireless Networks*, vol. 21, no. 5, pp. 1457-1472, July, 2015. Article (CrossRef Link)
[18] R. Liao, B. Bellalta, M. Oliver, and Z. Niu, "MU-MIMO MAC protocols for wireless local area networks: A survey," *IEEE Communications Survey & Tutorials*, vol. 18, no. 1, pp. 162-183, December, 2014. Article (CrossRef Link)
[19] W. H. Xi, T. Whitley, A. Munro, M. Barton, D. Kaleshi, and G. Heide, "Effectiveness of QoS provided by IEEE 802.11e for different traffic types," in *Proc. of IEEE 62nd Vehicular Technology Conference*, pp. 1132-1136, September 28, 2005. Article (CrossRef Link)
[20] R. Costa, P. Portugal, F. Vasques, C. Montez, and R. Moraes, "Limitations of the IEEE 802.11 DCF, PCF, EDCA and HCCA to handle real-time traffic," in *Proc. of IEEE 13th International Conference on Industrial Informatics*, pp. 931-936, July 22-24, 2015. Article (CrossRef Link)
[21] W. Sun, H. Zhang, C. Pan, and J. Yang, "Analytical study of the IEEE 802.11e EDCA mechanism," in *Proc. of IEEE Intelligent Vehicles Symposium*, pp. 1428-1433, June 23-26, 2013. Article (CrossRef Link)
[22] C. Zhu, A. Bhatt, Y. Kim, O. Aboul-Magd, and C. Ngo, "MAC enhancements for downlink multi-user MIMO transmission in next generation WLAN," in *Proc. of IEEE Consumer Communications and Networking Conference*, pp. 832-837, January 14-17, 2012. Article (CrossRef Link)
[23] M. Yazid, A. Ksentini, L. Bouallouche-Medjkoune, and D. Aissani, "Performance Analysis of the TXOP Sharing Mechanism in the VHT IEEE 802.11ac WLANs," *IEEE Communications Letters*, vol. 18, no. 9, pp. 1599-1602, July, 2014. Article (CrossRef Link)
[24] M. X. Gong, E. Perahia, R. Want, and S. Mao, "Training protocols for multi-user MIMO wireless LANs," in *Proc. of IEEE* 21st *International Symposium on Personal, Indoor and Mobile Radio Communications*, pp. 1218-1223, September 26-30, 2010. Article (CrossRef Link)
[25] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal Selected Areas in Communications*, vol. 18, no. 3, pp. 535-547, March, 2000. Article (CrossRef Link)
[26] T. Sakurai and H. L. Vu, "MAC access delay of IEEE 802.11 DCF," *IEEE Transactions on Wireless Communications*, vol. 6, no. 5, pp. 1702-1710, May, 2007. Article (CrossRef Link)



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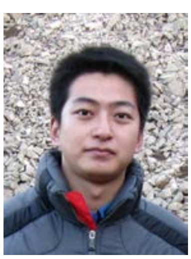

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