

Efficient Transmission Mode Selection Scheme for MIMO-based WLANs

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Abstract

While single-user spatial multiplexing multiple-input multiple-output (SU-MIMO) allows spatially multiplexed data streams to be transmitted to one node at a time, multi-user spatial multiplexing MIMO (MU-MIMO) enables the simultaneous transmission to multiple nodes. However, if the transmission time required to send packets to each node varies considerably, MU-MIMO may fail to utilize the available MIMO capacity to its full potential. The transmission time typically depends upon two factors: the link quality of the selected channel and the data length (packet size). To utilize the cumulative capacity of multiple channels in MIMO applications, the assignment of channels to each node should be controlled according to the measured channel quality or the transmission queue status of the node. A MAC protocol design that can switch between MU-MIMO and multiple SU-MIMO transmissions by considering the channel quality and queue status information prior to the actual data transmission (i.e., by exchanging control packets between transmitter and receiver pairs) could address such issues in a simple but in attractive way. In this study, we propose a new MAC protocol that is capable of performing such switching and thereby improve the system performance of very high throughput WLANs. The detailed performance analysis demonstrates that greater benefits can be obtained using the proposed scheme, as compared to conventional MU-MIMO transmission schemes.

Keywords: IEEE 802.11ac, IEEE 802.11n, MU-MIMO, SU-MIMO

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A preliminary short version of this paper appeared in AH-ICI2012, Nov 23-25, Kathmandu, Nepal. This version includes a concrete performance analysis considering effect of data length in the system performance along with detailed discussion of relevant technical issues such as precoding, efficient transmission mode selection procedure, and frame aggregation.

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1. Introduction

Multiple-input multiple-output (MIMO) antenna systems have been attracting increased interest [1], as MIMO improves the wireless channel capacity without requiring additional bandwidth or power. This enhanced capacity is derived from either the increased spectral efficiency or improved link reliability. Wireless networks deployed using MIMO systems can then utilize these features by employing spatial multiplexing and/or spatial diversity [2],[3].

With the IEEE 802.11n amendment, MIMO systems were introduced into the WLAN standard [4], such that the latest WLAN standard supports both spatial multiplexing and spatial diversity. For spatial multiplexing, however, the standard only supports single-user spatial multiplexing MIMO (SU-MIMO) transmission. SU-MIMO is a form of point-to-point MIMO communication in which all transmitted data streams are destined for a single receiver; the spectral efficiency linearly increases in conjunction with the number of antenna elements. However, SU-MIMO is not suitable for all network characteristics. For example, its application is not beneficial unless all queues of corresponding antenna elements have sufficient packets to send, or if the antenna elements are distributed evenly in a transmitter-receiver pair. Moreover, when it is applied under a WLAN default medium access control (MAC) protocol, i.e., carrier sense multiple access/collision avoidance (CSMA/CA), SU-MIMO is only advantageous when the transmitting node handles the data packets of one node at a time. Otherwise, if a transmitting node such as an access point (AP), attempts to handle the data packets of multiple nodes, it is necessary to make repeated independent transmission attempts, which ultimately increases the delay and reduces the throughput.

To overcome the disadvantages of SU-MIMO, there have been many studies of multi-user spatial multiplexing MIMO (MU-MIMO) transmissions [5]. MU-MIMO is a form of point-to-multipoint MIMO communication, in which independent data streams are destined for different receivers. MU-MIMO offers two significant advantages compared to SU-MIMO. First, MIMO-equipped transmitter nodes can initiate MU-MIMO transmissions, even when the receiver nodes are single-input single-output (SISO) equipped. Typically, MIMO-equipped transmitter nodes can only handle one SISO-equipped receiver node at one time, which is logically equivalent to SISO-SISO communication. However, the features of MU-MIMO allow multiple antennas to be fully utilized, thereby enabling higher performance gains, which can be considered logically as MIMO communications. Second, irrespective of the antenna configuration on the receiver side, MIMO-equipped transmitter nodes can initiate MU-MIMO transmissions if they need to connect with multiple nodes during the same transmission opportunity.

Theoretical and practical studies have demonstrated the superiority of MU-MIMO [6], such that the IEEE 802.11ac task group for very high throughput (VHT) WLAN has extended the latest high throughput WLAN standard to include MU-MIMO [7],[8]. However, despite its superiority, MU-MIMO still presents research challenges [9]. For instance, each data stream is encoded with respect to the channel quality of the corresponding node, in which a higher channel quality implies a greater transmission capacity and vice versa. As a result, the network performance is determined by the lowest per-link data rate. Indeed, if the channel quality between receiving nodes varies significantly, as shown in Fig. 1, MU-MIMO may fail to fully

utilize the available MIMO capacity. A similar problem can also arise because of the dynamic size of data packets; different applications may have different data lengths and each node could have a different link quality, such that the conjoint problem may severely degrade MU-MIMO transmissions. Thus, we propose a simple MAC protocol to overcome these issues and to maximize the utilization of available MIMO capacity in VHT WLANs.

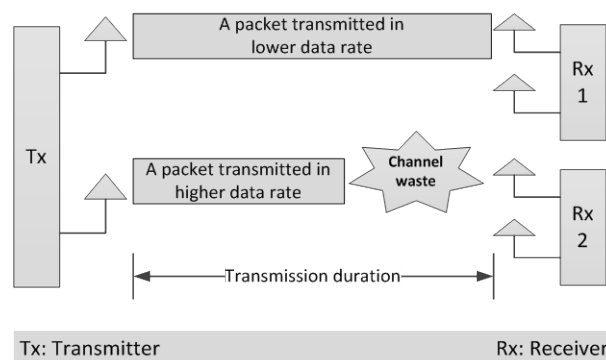


Fig. 1. Capacity loss caused by variable data rates in MU-MIMO

In addition to the general CSMA/CA MAC features, the proposed protocol acts as a switching entity between MU-MIMO and multiple SU-MIMO (mSU-MIMO) transmissions, in which mSU-MIMO includes multiple point-to-point MIMO communications during a single transmission opportunity (i.e., one after another). The MAC layer determines the appropriate transmission mode after estimating the performance outputs when relevant information is exchanged between transmitter-receiver pairs via the control packets.

The remainder of this paper is organized as follows. Section 2 presents background information about CSMA/CA, SU-MIMO, and MU-MIMO, and Section 3 then describes related research. Section 4 discusses the proposed scheme and its numerical analysis in detail. Section 5 presents our performance evaluation and future works, and Section 6 concludes the paper.

2. Background

2.1 CSMA/CA

WLAN supports shared access to wireless channels through a technique called CSMA/CA. In CSMA/CA, as the first step a node having a packet to send monitors the channel activity. The node continues its transmission if the channel is determined to be idle for an interval that exceeds the distributed interframe space (DIFS). Otherwise, the node waits until the channel becomes idle for the DIFS period and then computes a random backoff time for which it will defer its transmission. The defer time is the product of the selected backoff value and the slot duration. After the medium becomes idle for a DIFS, the nodes start to decrease their backoff timer until the channel becomes busy again or the timer reaches zero. If the timer has not reached zero and the medium becomes busy, the node freezes the timer. When the timer finally reaches zero, the node transmits its packet and waits for an acknowledgement (ACK). If the

receiver node successfully receives the packet, it sends ACK after a short interframe space (SIFS).

CSMA/CA is based on the principle of “*listen before talk*”. WLAN also supports another version of CSMA/CA, which is based on the principle of “*listen and reserve before talk*”. This second version is known as the CSMA/CA request to send/clear to send (RTS/CTS) mechanism. In this mechanism, if a node monitors the channel activity and finds it idle for more than the DIFS, the node sends a special reservation packet called the RTS, at which point the intended receiving node responds with the CTS. Other nodes that overhear the RTS and CTS update their network allocation vector (NAV¹) and wait until the reserved time has elapsed. The transmitting node is only allowed to transmit its packet if the CTS packet is received correctly.

2.2 SU-MIMO

SU-MIMO is a point-to-point MIMO communication technique. In this scheme, all received signals are available at a receiver for processing, which allows the receiver to easily determine the channel transfer matrix. After the channel transfer matrix is known, the transmitted data streams can be reconstructed by multiplying the received vector by the inverse of the transfer matrix [10]. For example, if the input signal x is linearly transformed by channel H to yield the output y , given H and disregarding the noise, the transmitted symbol vector x can be retrieved simply from the received signal vector y as $x = H^{-1}y$. However, to determine the channel H , a channel estimation procedure must precede the real data packet exchange. Therefore, to address this issue, IEEE 802.11n has upgraded CSMA/CA to SU-MIMO-aware CSMA/CA.

In SU-MIMO-aware CSMA/CA, the main extensions include changes in the frame control fields in the data packet headers and control packets. The legacy control packets are wrapped in the control wrapper frame, which include information about the ongoing modes of transmission (MIMO or SISO). Note that training fields² are included in the physical layer convergence protocol (PLCP) for channel estimation. Two types of training fields are used in IEEE 802.11n: the short training field is used for automatic gain control and time synchronization, and the long training field is used for channel estimation. The number of long training fields is equal to the number of data streams multiplexed by the transmitter.

2.3 MU-MIMO

In SU-MIMO, the benefit of MIMO processing is achieved via the coordination of processing among all transmitter or receiver antenna elements. In MU-MIMO, however, it is usually assumed that there is no coordination among the nodes, which can lead to inter-user interference problems. However, a capacity gain similar to SU-MIMO can be achieved in MU-MIMO provided that appropriate signal processing, also known as precoding, is applied prior to the data transmission (see Fig. 2). If channel state information (CSI) is available at the

¹ NAV was designed to sense virtual carriers.

² A training field is a fixed symbol specified in the standard, which is known to both the transmitter and the receiver.

transmitter, the inter-user interference can be mitigated using techniques such as intelligent beamforming or the use of dirty paper codes [11],[12].

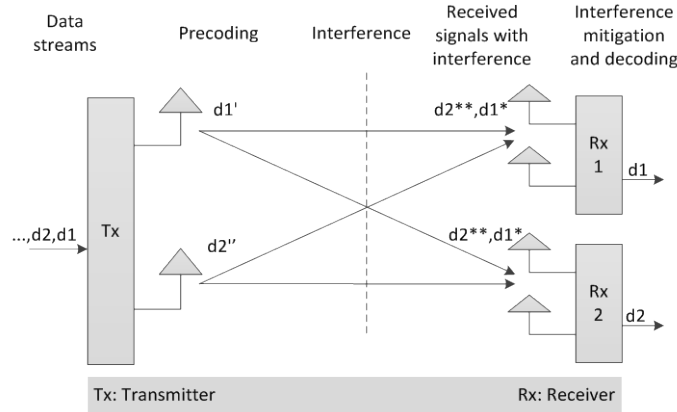


Fig. 2. MU-MIMO interference mitigation

Intelligent beamforming is a linear precoding technique. In brief, if we consider a MU-MIMO system with N transmitting and receiving antenna elements, the transmitter can transmit a total of N spatial streams. When the transmitter transmits different streams to different users, the stream intended for a specific user will create interference for the other users. For example, if signal x_i for user i is transmitted from antenna element i with signal weight w_i and channel coefficient h_i , it will create interference that affects all received signals. However, the transmitter can mitigate this interference by applying an intelligent beamforming technique. In this case, the signal weights are selected such that $h_i w_j = 0$ for $i \neq j$, which then cancels the interference from other users.

In contrast, the dirty paper coding technique is a nonlinear precoding technique based on the concept of “writing on dirty paper”. According to information theory, writing on dirty paper is equivalent to writing on clean paper if one knows where the dirt is located beforehand. During MU-MIMO transmission, the transmitter obtains CSI from all its receivers and thus knows the interference from users signals that can affect other users, which allows the transmitter to generate a specific signal for the other users that compensates for the known interference. For example, one dirty paper coding technique uses a QR decomposition of the channel, which can be represented as the product of a lower triangular matrix L and a unitary matrix such that $H = LQ$. The signal that needs to be transmitted is then precoded using the Hermitian transpose of Q , which results in channel L . Next, the first user of this system observes no interference from other users and a signal can be selected without considering the other users. The second user only observes interference from the first user, but as that interference is known it can be overcome using this coding technique; other signals are coded in a similar way.

To realize the advantages of MU-MIMO in existing WLANs, significant changes are required in order to upgrade conventional MAC protocols into MU-MIMO-aware MAC. This modification of conventional CSMA/CA-based MAC protocols is required in order to utilize the CSI from all intended receivers at the transmitter [13]. The draft version of IEEE 802.11ac has a provision for MU-MIMO transmission in the downlink of an infrastructure-based WLAN. In Fig. 3, if a node wishes to initiate MU-MIMO transmission, it broadcasts an RTS packet to multiple intended receivers by explicitly including their address information in series in the address field. Next, the receiver nodes reply using an individual CTS packet, which also contains the CSI, in the same serial order. After exchanging the control packets, the transmitting node determines the interference situation in the downlink based on its CSI and, using this knowledge, it applies precoding and sends parallel data streams. Finally, the receiver nodes that receive the data stream successfully acknowledge their reception by ACK packet transmission in the same order as the CTS transmissions.

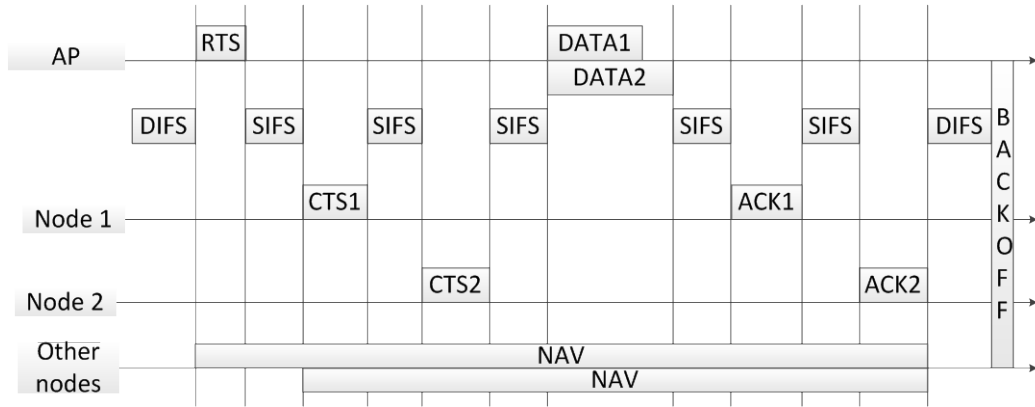


Fig. 3. MU-MIMO transmission in a 2×2 MIMO system

3. Related Works

A variety of MAC layer enhancement techniques in MU-MIMO deployed on WLANs have been investigated. For example, Tandi *et al.* [14] proposed a cross-layer-optimized user grouping strategy to optimize the MU-MIMO transmission duration. In this scheme, a primary user is initially selected based on their level of urgency for data delivery. Next, the user group that includes the primary user and has the maximum channel capacity is selected as targeted secondary users for MU-MIMO transmission. Finally, the packet sizes of the secondary users are adjusted to match the primary user's transmission time, based on fragmentation or aggregation. In this scheme, however, it is assumed that the precise CSIs of all receivers are known by the transmitter, which cannot be practically implemented without an additional feedback mechanism; i.e., if feedback is provisioned from all receivers, considerable overhead is incurred.

Cha *et al.* [15] compared the performance of downlink user multiplexing schemes based on IEEE 802.11ac, which compared the performance of an MU-MIMO transmission scheme with a downlink frame aggregation scheme. Here, the frame aggregation is similar to mSU-MIMO, in which the data packets of multiple users are concatenated and transmitted during a single transmission attempt. However, this study only focused on a performance analysis without

considering the MAC layer protocol design, the requirements for control packet modification, or the associated overhead and its effect on network performance.

And Zhu *et al.* [16] investigated problems with the downlink MU-MIMO MAC in IEEE 802.11ac in terms of transmit opportunity (TXOP³) sharing and subsequently proposed a simple solution for sharing TXOP among the primary access class (AC) and secondary ACs. In brief, after any AC (a particular data type for a particular receiver) wins a TXOP, it becomes the primary AC. The remaining ACs (the same or other data types for other receivers) then become the secondary ACs. The duration of the TXOP is determined by the TXOP limit of the primary AC, with the transmission time also determined by the amount of data that is scheduled to be transmitted by the primary AC. Thus, the transmission cycle in this scheme ends after the primary AC finishes its transmission, even if secondary ACs still have packets to send, or if the secondary links are silent if they finish early.

In contrast to these methods, we propose a simple yet practical CSMA/CA-based MAC protocol that supports switching between the MU-MIMO and mSU-MIMO transmissions, which thereby maximizes the efficiency of the MU-MIMO deployed by WLANs. The proposed scheme implementation only requires subtle modifications of the conventional MU-MIMO transmission scheme, which are discussed in the following section.

4. Proposed Protocol and Numerical Analysis

In the proposed MAC protocol, if a node wants to send data packets to multiple receivers, the node first acquires a channel using the CSMA/CA channel acquisition rule, similar to the pure MU-MIMO scheme mentioned above. However, after the transmitter receives the CTS packets, instead of immediately transmitting data it predicts the performance results for both the MU-MIMO and mSU-MIMO schemes. The transmitter can determine the channel qualities of all corresponding nodes, the required overhead associated with each scheme, and all data lengths to be transmitted to each receiver. The acquired information then allows the transmitter to estimate the possible performance of both schemes. If the transmitter decides to use mSU-MIMO, it sends the required information by broadcasting a new control packet, referred to as a new-RTS (RTSn⁴). Otherwise, the default MU-MIMO scheme is used with no changes. In the mSU-MIMO scheme, the node sends data streams in serial order, where each is separated by SIFS (Fig. 4); with MU-MIMO, parallel transmissions follow after SIFS.

Our numerical analysis follows a modular approach. First, we analyze the behavior of a single tagged node by formulating a single dimensional Markov model, as previously described [17]. Using the formulated model, the probability τ that a node starts to transmit in a randomly selected time slot is calculated. We then express the average throughput and average packet delay as a function of τ . For simplicity, the following assumptions are made: (a) the number of nodes in the network is finite (i.e., n), (b) the nodes always have packets to transmit, and (c) the channel is error-free. The probability τ can subsequently be derived using the default contention resolution algorithm, i.e., binary exponential backoff (BEB).

³ A TXOP is a bounded time interval (determined by the traffic class) during which a transmitting node can send as many packets as possible, unless the transmission duration exceeds the maximum time limit allowed.

⁴ RTSn plays a vital role because it allows nodes to update their NAV.

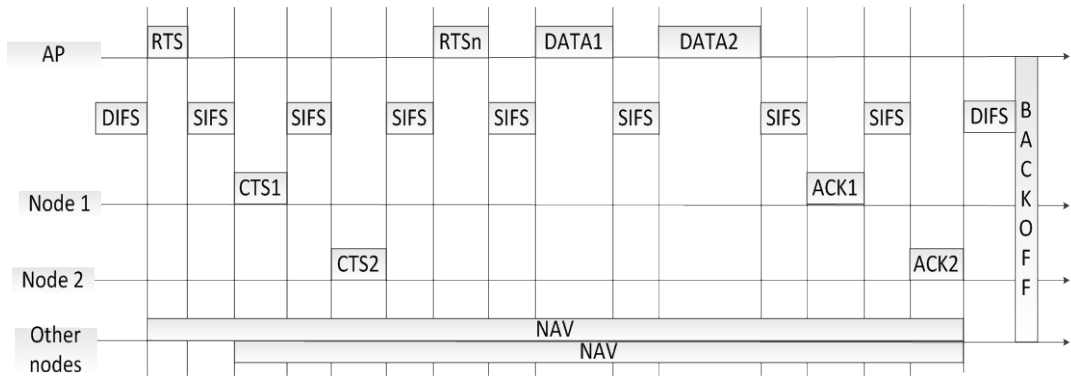


Fig. 4. mSU-MIMO transmission using a 2×2 MIMO system

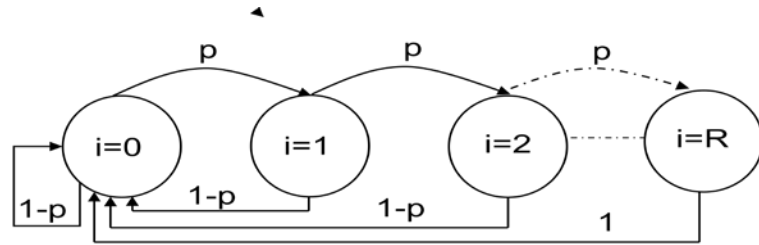


Fig. 5. Markov chain model

During MU-MIMO transmission, a collision occurs if two or more transmitters start their transmissions in the same time slot. If there is a collision, the colliding nodes randomly select backoff values from the contention window range using the BEB algorithm, and then wait until the values defer to 0 . The random value refers to the number of transmission opportunities that the node must give up before starting the next transmission. For example, let i be the number of contention states, $0 \leq i \leq R$, where R is the maximum allowed retransmission state, after which a node drops the packet. A transmitting node can then transition through the states up to state R by increasing the value of i by 1 during each successive collision. If a successful transmission occurs, the node resets its state to 0 . If we assume that SS_i is the i th state of a node after sending an RTS packet during state i , the node can either enter into the next state $i+1$ (i.e., SS_{i+1}) or 0 (i.e., SS_0), which depends on the success or collision of the transmitted packet, respectively. If we define p as the probability of collision, from the Markov chain analysis shown in Fig. 5, SS_i is the chain with the transition probabilities $p_{i,z}$; $i, z = 0, 1, \dots, R$, which can be expressed as follows.

$$p_{i,0} = \Pr\{SS_{i+1} = 0 \mid SS_i = i\} = 1 - p \quad (1)$$

$$p_{i,i+1} = \Pr\{SS_{i+1} = i+1 \mid SS_i = i\} = p \quad (2)$$

$$p_{R,0} = \Pr\{SS_0 = 0 \mid SS_R = R\} = 1 \quad (3)$$

Furthermore, τ is the relative frequency of entering state i , and is defined as [17]

$$\tau = \frac{1}{1 + \frac{1-p}{1-p^{R+1}} \sum_{i=0}^R p^i E[b_i]}, \quad (4)$$

where $E[b_i]$ is the average backoff time in contention state i . In addition, $E[b_i]$ for state i is $\frac{w_i}{2}$, where w_i is the maximum contention window size for state i .

In a stationary state, a node transmits a packet with probability τ . Thus, the collision probability p that the remaining $n-1$ nodes transmit in the same arbitrary time slot can be expressed as [18]

$$p = 1 - (1 - \tau)^{n-1}. \quad (5)$$

Equations (4) and (5) are nonlinear systems having two unknowns, τ and p , which can be solved using standard numerical methods to obtain a unique solution. After obtaining τ and p , performance metrics such as the throughput and delay can then be derived based on considerations of other system parameters.

4.1 Average Throughput

Throughput is defined as the rate of successful transmission of data bits over the channel. Thus, during MU-MIMO transmission the throughput S can be given as

$$S = \frac{P_s P_{tr} \sum_{j=1}^K E[P_j]}{(1 - P_{tr})T_i + P_s P_{tr} T_s + (1 - P_s)P_{tr} T_c}, \quad (6)$$

where P_{tr} is the probability that there is at least one active transmitting node in a given slot time and that P_s is the probability of successful transmission. Similarly, $E[P_j]$ is the payload size transmitted in channel j , $1 \leq j \leq K$, and $K \in [1, N]$. Note that P_{tr} and P_s can be easily obtained if τ and p are known [18].

$$P_{tr} = 1 - (1 - \tau)^n \quad (7)$$

$$P_s = \frac{n\tau(1 - \tau)^{n-1}}{P_{tr}} \quad (8)$$

In (6), T_s and T_c are the average times when the channel is found to be busy because of successful transmission or collision, respectively, whereas T_i is the duration of an empty slot.

In our investigation, T_s and T_c can be expressed as follows:

$$T_{s, \text{MU-MIMO}} = T_{DIFS} + T_{RTS} + (2K + 1)T_{SIFS} + KT_{CTS} + T_{DATA} + T_{ACK} \quad (9)$$

$$T_{s,mSU-MIMO_s} = T_{DIFS} + T_{RTS} + (3K+1)T_{SIFS} + KT_{CTS} + T_{RTS_n} + KT_{DATA} + KT_{ACK} \quad (10)$$

$$T_{c,MU-MIMO/mSU-MIMO_s} = T_{DIFS} + T_{RTS} \quad (11)$$

where $T_{(\cdot)}$ indicates the time required to send the respective frames.

4.2 Average Delay

Delay is defined as the interval from when a packet is at the head of its MAC queue waiting to be transmitted until ACK is received for that packet. The average packet delay D can be derived following the model in [17], which for our analysis can be expressed as

$$D = \frac{E[n]}{S / E[P]} \quad (12)$$

where $E[n]$ is the average number of nodes that will successfully deliver the packets, and $S / E[P]$ is the packet delivery rate. Note that some packets that are ready to be delivered could drop out during the transmission process, thus $E[n]$ can be defined as

$$E[n] = n[1 - P_{drop}] \quad (13)$$

where P_{drop} is the packet drop probability attributable to exhaustion of the retry limit, i.e. [17],

$$P_{drop} = \tau(1-p) \frac{p^{R+1}}{1-p^{R+1}} \sum_{i=0}^R (1 + E[b_i]) \quad (14)$$

Finally, based on the relations above, D can be expressed as

$$D = \frac{n}{S / E[P]} - E[Slot](1 - B_0) \frac{p^{R+1}}{1-p^{R+1}} \sum_{i=0}^R (1 + E[b_i]) \quad (15)$$

where \bar{S} is the throughput of the corresponding antenna element while $E[Slot] = (1 - P_{tr})T_i + P_s P_{tr} \bar{T}_s + (1 - P_s)P_{tr} T_c$, where \bar{T}_s is the average of the successful transmission times for the respective antenna elements, and $B_0 = 1/(W_0 + 1)$.

4.3 Efficient Transmission Mode

The transmission duration associated with each transmission mode is known after the control packets are successfully exchanged; the total overhead associated with each transmission mode can also be computed from this information. Thus, because all other channel access parameters remain constant, the switching criterion can be established as follows.

Let the throughput ratio α between two transmission modes be defined as

$$\alpha = \frac{S_{MU-MIMO}}{S_{mSU-MIMO}}. \quad (16)$$

Then, if the throughput is a primary concern, the selection of the transmission mode is performed such that

```

if  $\alpha \leq 1$  then
    select  $mSU - MIMO$ 
else
    select  $MU - MIMO$ 
endif.

```

Likewise, we can define the delay ratio β between two transmission modes if the delay is an important concern, with the selection of an efficient transmission mode following a similar procedure.

$$\beta = \frac{D_{MU-MIMO}}{D_{mSU-MIMO}} \quad (17)$$

Likewise, we can consider the product of α and β as a selection criterion, and perform a similar selection procedure if both the throughput and delay are important concerns.

5. Performance Evaluation

We numerically evaluated the performance based on the equations above and the parameters presented in [Table 1](#) [4]. The selected parameters were obtained from IEEE 802.11n, with subtle modifications. The control frame formats are presented in [Fig. 6](#), where the RTS and CTS packets have been modified from their conventional forms to append information regarding the receiver addresses and CSI, respectively. We assumed a 2×2 MU-MIMO transmission throughout this analysis. In addition, the RTSn frame was assumed to contain information about the ongoing transmission mode in its PLCP header.

In our analysis, we considered the frame aggregation scheme defined in IEEE 802.11n in order to indicate the difference in data length. Similarly, the modulation and coding schemes (MCS) were used to indicate the variable link quality, as shown in [Table 2](#) [4]. Note that frame aggregation is a technique that packs two or more frames into a single frame before transmitting them in a single TXOP. IEEE 802.11n introduced this scheme in WLAN to reduce the PHY and MAC layer overhead when transmitting multiple packets during a single transmission opportunity. IEEE 802.11n makes a provision for two types of aggregation schemes: aggregate MAC service data unit (A-MSDU) and aggregate MAC protocol data unit (A-MPDU) [19]. The forthcoming WLAN IEEE 802.11ac will also include these schemes, although with different specifications.

In A-MSDU, two or more MSDUs are aggregated to form a single MPDU. Each A-MSDU comprises several subframes, each of which has a separate MSDU. However, the final MPDU size is limited to a maximum of 7,955 bytes in IEEE 802.11n and 11,456 bytes in IEEE 802.11ac (according to the IEEE 802.11ac draft version [20]). In the A-MPDU scheme, two or more MPDUs having common PHY headers are aggregated. Again, each A-MPDU comprises several subframes, each of which has a separate MPDU. However, the A-MPDU length should not be greater than 64 KBytes in IEEE 802.11n, whereas it is 1,048,576 bytes in IEEE 802.11ac. In our analysis, we considered an A-MSDU aggregation scheme in which the MSDU size was fixed at 1500 bytes.

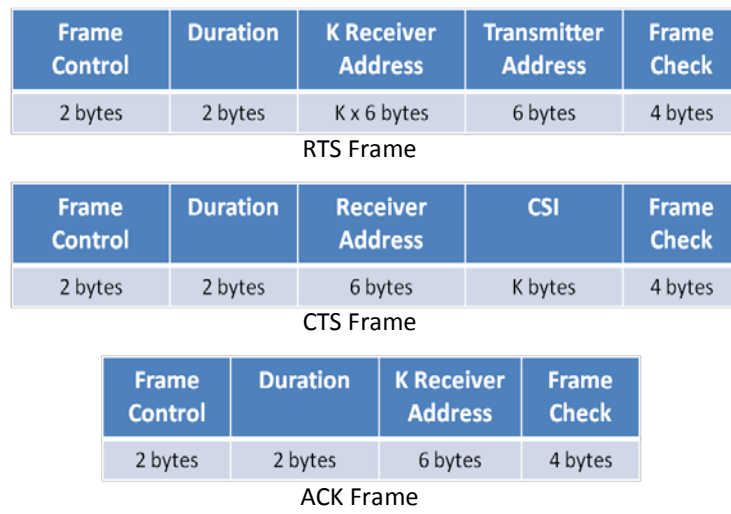


Fig. 6. Control frame formats

Table 1. System Parameters

Parameters	Value
DIFS	34 μ s
SIFS	16 μ s
Slot time	9 μ s
PHY header	40 μ s
MAC header	272 bits
RTS packet	208 bits
CTS packet	128 bits
ACK packet	112 bits
RTSn packet	208 bits
Basic data rate	6.5 Mbps
Minimum contention window (W)	16
Maximum retry (R)	6

Table 2. IEEE 802.11 Modulation and Coding Schemes (bandwidth 20 MHz)

MICS index	Spatial stream	Modulation rate	Coding rate	Data rate (Mbps)
0	1	BPSK	1/2	6.5
1	1	QPSK	1/2	13
2	1	QPSK	3/4	19.5
3	1	16-QAM	1/2	26
4	1	16-QAM	3/4	39
5	1	64-QAM	2/3	52
6	1	64-QAM	3/4	58.5
7	1	64-QAM	5/6	65
...				
15	2	64-QAM	5/6	130
...				
31	4	64-QAM	5/6	260

The average throughputs with respect to the number of nodes when the receiver nodes had different data rates are presented in Fig. 7, which shows that the throughput increased initially as n increased and then started to decrease after reaching a specific threshold. This is because, at initial, when there were fewer number of nodes in the network, the probability of slots remaining idle (due to backoff) was high. But when the number of nodes increased, the probability of slots remaining idle reduced and as a result the throughput increased. However, when n passed the threshold level, the probability of collision started to increase and the throughput reduced. Furthermore, the throughput was seen to increase with the data rate, as the increased data rate reduced the transmission duration.

In addition to these general observations, it can also be observed that for the set of MCSs (BPSK 1/2, QPSK 1/2), (BPSK 1/2, 16-QAM 1/2), (BPSK 1/2, 64-QAM 2/3), (QPSK 1/2, 16-QAM 1/2), and (QPSK 1/2, 64-QAM 2/3), the throughput performance with mSU-MIMO transmission was higher than for MU-MIMO. In contrast, with the MCS option (16-QAM 1/2, 64-QAM 2/3) the throughput performance was similar. Using the MCS option (16-QAM 3/4, 64-QAM 2/3), the throughput performance was lower with mSU-MIMO than MU-MIMO. These results demonstrate the effect of throughput dependency at a lower data rate for MU-MIMO, while also illustrating the throughput dependency on all the data rates for mSU-MIMO.

The average delay performance using the same network scenarios is presented in Fig. 8, which shows that the delay increased with the number of nodes. It is clear that as the number of nodes increased, the collision probability increased and that ultimately increased the delay. However, the delay decreased with an increase in the data rate, because the increased data rate reduced the transmission time. Furthermore, these results also show that the delays for the sets of MCSs (BPSK 1/2, QPSK 1/2), (BPSK 1/2, 16-QAM 1/2), (BPSK 1/2, 64-QAM 2/3), (QPSK 1/2, 16-QAM 1/2), and (QPSK 1/2, 64-QAM 2/3) were lower with mSU-MIMO. In contrast, the delays were higher when using the MCS option (16-QAM 3/4, 64-QAM 2/3).

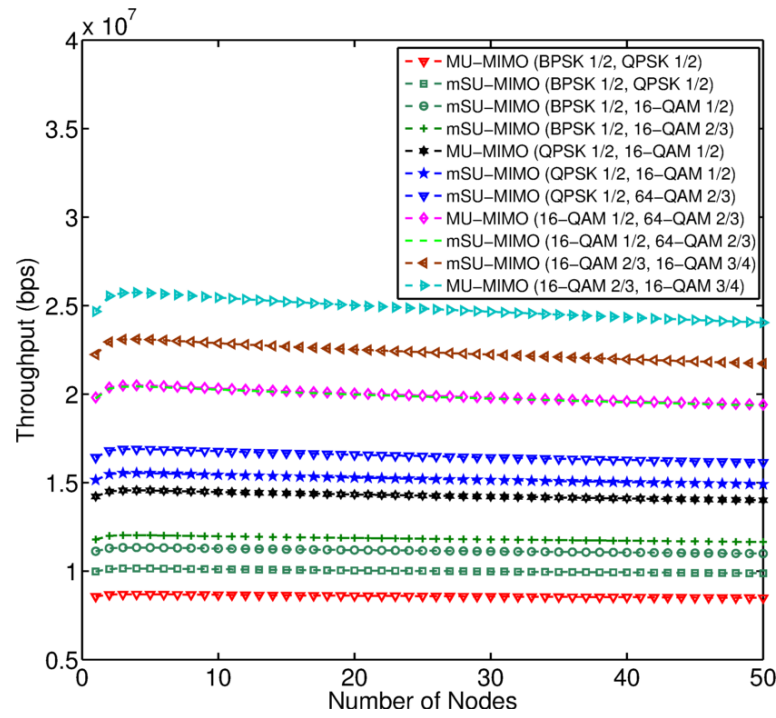


Fig. 7. Average throughput depending on the number of nodes

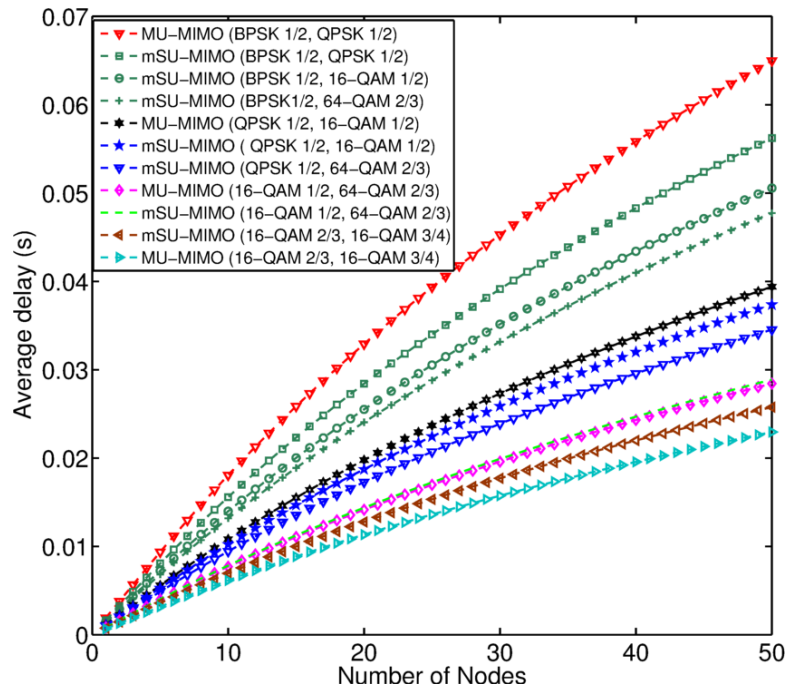


Fig. 8. Average delay depending on the number of nodes

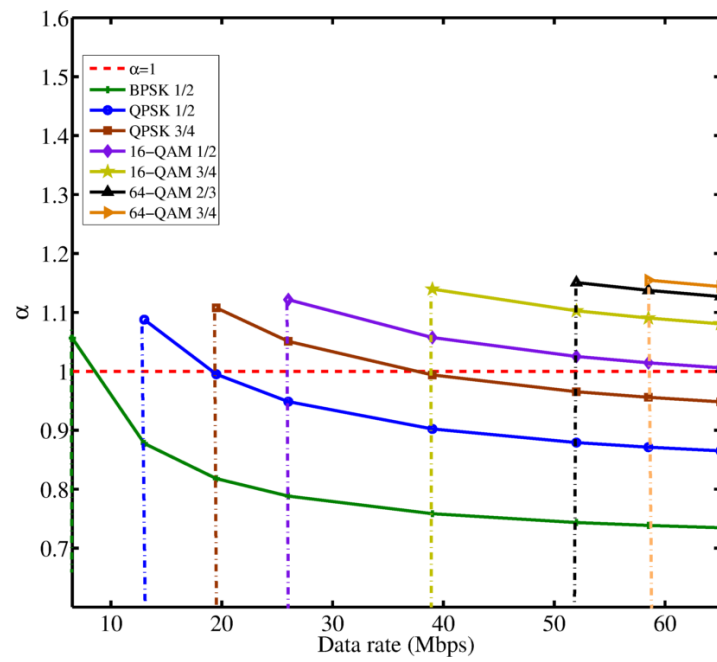


Fig. 9. Criterion α with respect to the MCS options for each data rate

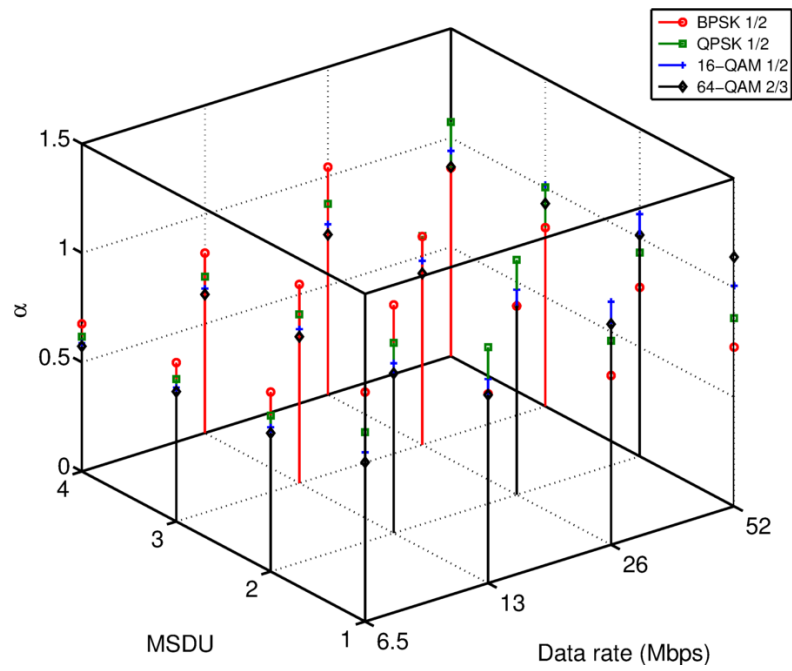


Fig. 10. Criterion α with respect to the data rate and length

Fig. 9 shows the criterion for the mode change with respect to the MCSs for all data rates, where only the link quality was considered, whereas **Fig. 10** shows the same criterion based on considerations of the link quality and data length.

Based on this analysis, it can be concluded that the proposed protocol facilitates the establishment of a switching criterion, which provides many benefits. The transmitting node can easily make a decision about the mode of transmission to adopt after analyzing the feedback information obtained from the corresponding control packets. Furthermore, this protocol can be extended to present the performance analysis when considering an error prone channel. The analysis can also be extended to investigate the overall system performance when implementing massive MIMO systems [21].

5. Conclusion

In this study, we proposed a new MAC protocol for selecting the most efficient transmission mode from MU-MIMO and mSU-MIMO. The scheme is simple and its implementation only requires a subtle modification of the conventional CSMA/CA MAC protocol used in current WLANs. Importantly, when compared to standard MU-MIMO transmission schemes, the proposed scheme is capable of maximizing the available MIMO capacity, especially when each receiver node has a different data rate or data length in each TXOP. Based on analytical observations, we showed that the application of the proposed scheme improved the throughput and reduced the delay in VHT WLANs compared to existing MU-MIMO transmission schemes.

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