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Performance Analysis and Enhancement of MIMO aware MAC Protocols in WLANs

Graduate School of Chosun University

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Advisor: Assoc. Prof. Seokjoo Shin

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ABSTRACT

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Multiple Input Multiple Output (MIMO) is a radio communication technology that uses multiple antenna elements at both transmitting and receiving ends. Multiple antenna elements in MIMO systems could be exploited to boost up channel capacity or to attain transmission reliability without additional bandwidth and power. Wireless networks deployed with MIMO systems can utilize these features by employing spatial multiplexing and/or spatial diversity.

Recently, MIMO systems have gained increased interest. Most of the existing wireless networks are looking forward to meet their ever increasing capacity demand by exploiting MIMO offered spectral efficiency. With the IEEE 802.11n amendment, MIMO systems have already been introduced to Wireless Local Area Networks (WLANs). IEEE 802.11n supports both spatial multiplexing and spatial diversity.

Regarding spatial multiplexing, however, the latest WLAN stan-

dard only supports Single User spatial multiplexing based MIMO (SU-MIMO) transmission. SU-MIMO is point-to-point MIMO communication, where all concurrently transmitted data streams are destined for a single receiver. But due to various network characteristics, SU-MIMO is not always applicable. For instance, unless all the queues of corresponding antenna elements have enough packets to send, it's not worth applying SU-MIMO. In addition, SU-MIMO is worthy only when the antenna elements are evenly distributed in a transmitter-receiver pair. Apart from that, SU-MIMO is advantageous mostly when the transmitting node also deals with data packets of only one node at a time. Otherwise, if a transmitting node deals with data packets of various nodes, like Access Point (AP), it requires to go through multiple transmission attempts, which ultimately increases delay.

To deal with inexpedient issues of SU-MIMO, Multi-User spatial multiplexing based MIMO (MU-MIMO) transmission is being widely studied. MU-MIMO refers to point-to-multipoint MIMO communication or vice versa. In downlink, it is point-to-multipoint MIMO communication, whereas, in uplink, it is multipoint-to-point MIMO communication.

Realizing MU-MIMO in existing WLANs requires significant changes in the MAC protocol. Either dominant MAC protocol Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) needs to be replaced by novel MU-MIMO aware MAC protocol or it should be upgraded into MU-MIMO aware CSMA/CA. Nevertheless, the simplest approach would be upgrading the widely deployed CSMA/CA. Therefore, in this dissertation, we investigate different modification approaches that best represent the possible modifications in CSMA/CA to upgrade it into MU-MIMO aware CSMA/CA. We consider both uplink and downlink MU-MIMO communications. We also provide detailed performance analysis to understand their performance benefits and trade-off.

As both theoretical and practical understanding have already shown the superiority of MU-MIMO in many cases, MU-MIMO can be expected to become one of the basic essentials of future wireless networks. Even so, MU-MIMO still has some limitations. For example, when the data transmission duration varies between the links due to difference in link quality or data length, MU-MIMO may fail to utilize the available MIMO capacity to its full potential. Therefore, in this dissertation, we also analyze a MAC layer solution to address such issues. We present a MAC layer protocol design that can switch between MU-MIMO and multiple SU-MIMO transmissions. After taking into account the achievable performance, presented protocol selects a transmission mode in such a way that the available MIMO capacity is maximally utilized.

요약

무선 LAN 시스템에서 MIMO aware MAC 프로토콜 성능 특성 및 개선 연구

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MIMO (Multiple Input Multiple Output)는 송수신기 양단에 다수의 안테나 엘리먼트를 사용하여 패킷 송수신을 수행함으로써 채널 용량을 증가시키거나 전송 신뢰도를 향상시키는 다중 안테나 기술이다. MIMO 시스템을 적용한 무선 네트워크는 공간 다중화 혹은 공간 다이버서티 특성을 적용하여 이러한 이점을 활용할 수 있다.

최근에 MIMO 시스템은 큰 관심을 얻고 있다. 대부분의 무선 네트워크는 높은 주파수 효율을 제공할 수 있는 MIMO 기술로부터의 사용자들의 용량 증대 요구를 만족시킬 수 있을 것으로 기대한다. IEEE802.11n 에서 보여지듯이 MIMO 시스템은 무선랜 (Wireless Local Area Networks)에 이미 적용되고 있다. IEEE802.11n 은 공간 다중화 및 공간 다이버서티 기법을 모두 제공한다.

그러나, 공간다중화 관점에서 최근의 WLAN 표준은 MIMO 기반의 단일 사용자 공간 다중화 (Single User MIMO or SU-MIMO) 전송 방식 만을 지원한다. SU-MIMO 는 점대점 MIMO 통신이며 이때 모든 송신 데이터 스트림은 단일 수신기로 전송된다. 그러나, 다양한 네트워크 특성으로 인하여 SU-MIMO 는 항상 효율적이지는 못하다. 예를 들어, 전송 안테나 엘리먼트 각각에 해당되는 큐에 전송을 위한 충분한 패킷이 없는 경우 SU-MIMO 의 장점이 희석될 수 있다. 또한, SU-MIMO 는 안테나 엘리먼트들이 송수신 쌍에 균등히 분산되어 있는 경우에만 효율적이다. 송수신노드 관점에서 SU-MIMO 는 전송 노드가 단지 하나의 수신 노드에 대하여 전송할 패킷을 처리하는 경우에 한 해 이점을 가진다. 만약 AP(Access Point)와 같은 하나의 전송 노드가 다수의 수신 노드들에 대한 패킷 전송을 처리하는 경우에는 순차적으로 다중 전송 시도를 수행하여야 하며 이는 극단적으로 지연을 증가시킨다.

SU-MIMO 기법의 단점을 해결하기 위하여 MIMO 기반의 다중 사용자 공간다중화 (MU-MIMO) 전송 기법이 광범위하게 연구되고 있다. MU-MIMO 는 점대다점 (Point to Multipoint) 통신을 의미한다. 하향링크로는 점대다점 MIMO 통신이, 상향링크로는 다점대점 MIMO 통신 기법이 적용된다.

현재의 WLAN 시스템에 MU-MIMO 를 적용하기 위해서는 MAC 프로토콜에 대한 많은 변화가 요구된다. 이를 위하여

CSMA/CA(Carrier Sense Multiple Access/Collision Avoidance) MAC 프로토콜을 MU-MIMO aware MAC 프로토콜로 대치하거나, MU-MIMO aware CSMA/CA 프로토콜로 업그레이드 하는 방식을 고려할 수 있으며, 쉬운 접근 방법은 CSMA/CA 를 기반으로 업그레이드하는 방법이다. 따라서, 본 논문에서는 통상적인 CSMA/CA 프로토콜을 MU-MIMO aware CSMA/CA 프로토콜로 업그레이딩하기 위한 다양한 변형 방안을 제시하였다. 또한, 상하향링크에 대한 MU_MIMO 통신 방식을 고려하여 상세한 수리적 분석을 통한 성능 이점과 트레이드오프 관계를 조명하였다.

MU-MIMO 기술에 대한 이점은 이론적, 실현적 관점에서 많이 연구되어 왔으며, MU-MIMO 기술은 미래 무선 네트워크의 가장 기본적 요소로 기대를 모으고 있다. 그러나 여전히 MU-MIMO 기술에 대한 제약 조건이 존재한다. 예를 들어 데이터 길이와 링크의 품질 차이에 따른 링크들 간의 데이터 전송 지속 시간이 변화하는 경우 MU-MIMO 의 최대 가능 용량까지 활용하기에는 어려움이 있다. 따라서 본 논문에서는 MAC 관점에서 이러한 문제를 해결하기 위한 방안을 분석하였다. 구체적으로 MU-MIMO 와 다중 SU-MIMO 전송을 적절하게 스위칭 할 수 있는 MAC 프로토콜 디자인을 제안하였으며, 성능 평가 도구로 획득 가능 성능(Achievable performance)을 고려하여 가용한 MIMO 용량을 최대화할 수 있는 전송 모드 선택 프로토콜을 제안하고 분석하였다.

Contents

Accronyms

A-MPDU	Aggregate MAC Protocol Data Unit
A-MSDU	Aggregate MAC Service Data Unit
AP	Access Point
BACK	Block ACK
BEB	Binary Exponential Backoff
BSS	Basic Service Set
CCK	Complementary-Code Keying
CRC	Cyclic Redundancy Check
CSI	Channel State Information
CSIF-STCP	CSI Feedback From Serially Transmitted CTS Packets
CSIP-SmTCP	CSI Prediction From Simultaneously Transmitted CTS Packets
CSIP-STCP	CSI Prediction From Serially Transmitted CTS Packets
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CTS	Clear To Send
DBPSK	Differential Binary Phase Shift Keying
DCF	Distributed Coordination Function
DIFS	Distributed Inter Frame Space
DLL	Delay Lower Limit
DQPSK	Differential Quadrature Phase Shift Keying

DR	Data Rate
DSP	Digital Signal Processing
DSSS	Direct Sequence Spread Spectrum
EDCA	Enhanced Distributed Channel Access
ETSI	European Telecommunication Standardization Institute
F-BACK	BACK for Forwarded Data
FCS	Frame Check Sequence
F-DATA	Forwarded Data
FHSS	Frequency Hopping Spread Spectrum
HT	High Throughput
IFS	Interframe Space
ISM	Industrial, Scientific and Medical
ISO	International Organization for Standardization
MAC	Medium Access Control
M-ACK	MIMO-ACK
M-CTS	MIMO-CTS
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MMSE	Minimum Mean Square Error
M-RTS	MIMO-RTS
MU-MIMO	Multiuser-MIMO
NAV	Network Allocation Vector

OFDM	Orthogonal Frequency Division Multiplexing
PDAs	Personal Digital Assistants
PHY	Physical Layer
PLCP	Physical Layer Convergence Protocol
QoS	Quality of Service
R-BACK	Reverse BACK
R-DATA	Reverse Data
RTS	Request To Send
RX	Receiver
SISO	Single Input Single Output
SIMO	Single Input Multiple Output
SNR	Signal to Noise Ratio
SU-MIMO	Single User multiplexing based MIMO
TDD	Time Division Duplex
TG	Task Group
TUL	Throughput Upper Limit
TX	Transmitter
TXOP	Transmission Opportunity
VTH	Very High Throughput
WLANs	Wireless Local Area Networks
WMANs	Wireless Metropolitan Area Networks
WPANs	Wireless Personal Area Networks

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1 Introduction

1.1 Background

By using radio waves, wireless networking technology provides flexible network connectivity to the network entities without relying on physical connection such as cables or wires. Ever since the world's first wireless packet data network, popularly known as ALOHANET [1], was developed at the University of Hawaii, in 1971, wireless networking technologies have advanced rapidly. Several wireless networks with diverse scope, range, and applications have been developed thenceforward. For example, Wireless Metropolitan Area Networks (WMANs) [2], Wireless Local Area Networks (WLANs) [3], and Wireless Personal Area Networks (WPANs) [4].

Wireless networks not only provide network users the freedom of mobility but also reduce network deployment costs. The last decade has witnessed tremendous growth in the wireless networking market. For example, WLANs currently supplement or replace wired networks in many homes, enterprises, and campuses. This paradigm shift is coupled with decreasing cost of WLANs networking equipments, gradual increment in WLANs data rates [5],[6], user's need for mobility, and the proliferation of digital appliances such as laptops, smart phones, and Personal Digital Assistants (PDAs). By 2012, some analysts are forecasting that more than one billion WLANs devices will be shipped globally every year [7].

WLANs have achieved great success on transition of wired home or office networks to wireless networks and have been widely deployed. However, WLANs suffer from different problems, such as channel fading, limited bandwidth, low power transmission requirements, and collision among the users. As such, WLANs have always been criticized for limited data rate in comparison to the wired line networks.

To satisfy higher data rate demand in WLANs, the IEEE 802.11 standards committee, under whose auspices the WLANs are standardized, formed a work group called IEEE 802.11n work group on 2003. The work group had a set up goal to bring some amendments on former IEEE 802.11 standards that could satisfy throughput performance equivalent to the counterpart wired line network. The work group came up with the first formal version of ratified amendment after six years, in 2009, that could satisfy Physical layer (PHY) throughput upto 600 Mbps and Medium Access Control (MAC) layer throughput upto 200 Mbps [8]. The newer standard introduced major modifications on both PHY and MAC layer specifications. Especially in PHY it introduced Multiple Input Multiple Output (MIMO) antenna systems while in MAC it supported enhanced MAC protocol features like frame aggregation, Block Acknowledgement (BACK), and bi-directional data flow [9].

1.1.1 MIMO in WLANs

Among different amendments brought in by IEEE 802.11n amendment, introduction of MIMO systems is considered as a major innovative step[1]. MIMO is a radio communication technique that uses multiple antenna elements at both transmitting and receiving ends either to boost up channel capacity or to attain transmission reliability without using additional bandwidth and power. Wireless networks deployed with MIMO systems can enjoy these features by employing spatial multiplexing and/or spatial diversity [10],[11]. Spatial multiplexing linearly increases PHY data rate with number of antenna elements, as it can transmit independent data streams concurrently from all antenna elements in same time and frequency domain. While, implementation of spatial diversity, which transmits a same data stream from multiple antenna elements, results into robust link setup [12],[13].

1.1.2 MIMO aware MAC protocols in WLANs

With the IEEE 802.11n amendment, WLANs have already included MIMO systems in PHY specification. However, from network point of view, only an increased capacity in one specific layer is not sufficient to improve an overall network performance. Moreover, each layer must be aware of the changes that have occurred in conjugate layers and their

[1]Few of the MAC enhancement techniques were already introduced in IEEE 802.11e standard and were only upgraded in IEEE 802.11n

applied protocols must be smart enough to realize the resulting effects positively. Hence, even though the implementation of MIMO systems can boost up PHY capacity, such an independently increased capacity cannot be translated easily into MAC layer capacity gain unless applied MAC protocol is also MIMO aware.

Simply, MIMO aware MAC protocol can be viewed as a protocol that possesses capability to apply some special measures at MAC layer, subject to maximizing the use of MIMO capacity at PHY. Such measures are crucial especially to address some MAC layer issues such as MIMO functionalities information exchange between transmitter-receiver pair, scheduling of enhanced bandwidth, and time synchronization. When applying such measures, it is also equally important to ensure backward compatibility to facilitate coexistence of legacy devices with only Single Input Single Output (SISO) antenna systems. Applying such measures is relatively easier in the networks with centralized control architecture like cellular networks, where highly sophisticated centralized administration unit can govern the medium access procedure and take control over resource allocation and utilization [14]. However, applying such measures is more challenging in case of distributed wireless networks like WLANs, where medium access is controlled by an asynchronous random access mechanism known as Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) [15].

Realizing the advantages of MIMO system over existing WLANs requires significant changes in MAC protocol. Either the dominant MAC protocol CSMA/CA needs to be replaced by novel MIMO aware MAC protocol or it should be upgraded into MIMO aware CSMA/CA. Nevertheless, the simplest approach would be upgrading the widely deployed CSMA/CA. An appropriately modified control packets exchange provisioned with an adequately carried out channel access mechanism based on CSMA/CA can upgrade it into a simple yet practicable MIMO aware MAC protocol. IEEE 802.11n has also provisioned MIMO aware MAC protocol by upgrading CSMA/CA. A control frame called control wrapper frame has been defined for this purpose. Control packets are wrapped within the control wrapper frame and then exchanged between transmitter and receiver. For example, Request To Send/Clear To Send (RTS/CTS) packets wrapped by control wrapper frame are used for request and feedback purposes.

MIMO aware MAC protocol in the IEEE 802.11n has been designed to support Single User spatial multiplexing based MIMO (SU-MIMO) transmission only (SU-MIMO aware MAC). SU-MIMO is a point-to-point MIMO communication, where all concurrently transmitted data streams are destined for a single receiver only. But noteworthy point is that due to various network characteristics, SU-MIMO is not always applicable. For instance, unless all the queues of corresponding antenna elements have enough packets to send, it's not worth applying SU-MIMO. In addition, SU-MIMO is worthy only when the antenna elements are evenly distributed in a transmitter-receiver pair. Apart from that, when applied with WLANs default MAC protocol CSMA/CA, SU-MIMO is advantageous mostly if the transmitting node also deals with data packets of a only one node at a time. Otherwise, if a transmitting node deals with data packets of various nodes, like Access Point (AP), it requires to go through multiple transmission attempts, which ultimately increases delay. Basically, in conventional CSMA/CA, each time a node wants to send data it has to contend for the channel and at each transmission opportunity it can connect to only one node. Likewise, in every transmission attempt bandwidth is also occupied by different overheads, e.g. transmission overhead (overheads due to transmission of PHY headers, MAC headers, control packets) and contention overhead (overheads due to waiting time during Interframe Spaces (IFSs) and backoff).

In order to deal with the above stated issues in WLANs, recently, Multi-User spatial multiplexing based MIMO (MU-MIMO) transmission is being widely studied [16]-[18]. MU-MIMO refers to point-to-multipoint MIMO communication or vice versa. In downlink, it is point-to-multipoint MIMO communication, whereas, in uplink, it is multipoint-to-point MIMO communication.

1.1.3 MU-MIMO in WLANs

As stated above, MU-MIMO is a point-to-multipoint MIMO communication or vice versa. If a transmitting node with multiple antenna elements transmits multiple independent data streams to multiple receiver nodes with/without multiple antenna elements in downlink, it is point-to-multipoint MIMO communication. Whereas, if a receiving node with multiple antenna elements receives multiple independent data streams from multiple transmitters with/without multiple antenna elements in uplink, it is multipoint-to-point MIMO communication.

MU-MIMO offers two significant advantages over SU-MIMO. First, even though receiving nodes are only equipped with legacy SISO antenna systems, MU-MIMO transmission can be established if transmitting node is MIMO equipped (and vice versa). Second, irrespective of SISO/MIMO capabilities in receiving side, MIMO node can start MU-MIMO transmission if it requires to send data packets to multiple nodes in the same transmission opportunity.

Although high practical importance of MU-MIMO has been shown both theoretically and practically, MU-MIMO has not been standardized yet in WLANs standard. Again, realizing the advantages of MU-MIMO in existing WLANs also requires significant changes in its MAC protocol. Either the dominant MAC protocol CSMA/CA needs to be replaced by a novel MU-MIMO aware MAC protocol or it should be upgraded into MU-MIMO aware CSMA/CA. Nevertheless, a simplest approach again would be upgrading the widely deployed MAC protocol. Therefore, in this dissertation, we investigate different modification approaches that best represent the possible modifications in CSMA/CA and provide detailed performance analysis to understand their performance benefits and trade-off. We consider both uplink and downlink MU-MIMO communications. Apart from that, when data transmission duration varies between the links due to difference in link quality or data length, MU-MIMO may fail to utilize the available MIMO capacity to its full potential. Therefore, in this dissertation, we also present a MAC layer solution to address such issues.

1.2 Contributions of Dissertation

This dissertation aims at contributing to the field of MIMO communication in distributed wireless networking, especially with focus on WLANs. In particular, among seven dedicated layers of wireless networking protocol suite, focus of this study is on the MAC sub-layer of the data link layer. In particular, we present performance analysis of MIMO aware MAC protocols and some innovative approaches to improvise their performance in a standard-complaint way without abolishing the original simplicity.

The first contribution of this dissertation is dedicated to performance analysis of SU-MIMO aware MAC protocol in WLANs, a MIMO aware MAC protocol introduced by IEEE 802.11n amendment [19]. In particular, IEEE 802.11n has brought different modifications to PHY and MAC layer specifications of the original IEEE 802.11 standard to address ever increasing demand of higher throughput. It not only has introduced MIMO technology at PHY layer, but also various features like frame aggregation, bi-directional data flow, and block acknowledgement at MAC layer. Adoption of MIMO technology in PHY layer boosts up the raw channel data rate while the enhanced MAC features mitigate transmission overheads. Various analytical and empirical studies have attempted to characterize the effects of such PHY and MAC enhancements in the overall performance of a network. To supplement those studies, in this dissertation, we analyze the bounding (maximum achievable) performance of such enhancement techniques. We consider throughput and delay performance measures.

The second contribution of this dissertation is dedicated to the performance characterization of CSMA/CA adapted MU-MIMO aware MAC protocols in WLANs [20]-[22]. In particular, as stated above, to realize MU-MIMO advantages over existing WLANs, it requires significant changes in MAC protocol and the simplest approach would be upgrading the widely deployed CSMA/CA. Simple modifications in control packets format and/or channel access mechanism can upgrade CSMA/CA into simple, yet practicable, MU-MIMO aware MAC protocol. By utilizing convenient changes, several modification approaches can be provisioned for this purpose. But, at the same time, it also becomes important to understand their performance benefits and trade-offs. In this dissertation, we discuss some of such modification approaches that best represent the possible modifications. We provide their detailed performance analysis based on analytical modeling in terms of throughput and delay. We also derive expressions for achievable performance analysis and present their performance limits too. We consider both the uplink and downlink MU-MIMO [23] communication.

Finally, the last contribution of this dissertation is dedicated to the MAC protocol design so as to select the efficient transmission mode in Very High Throughput (VHT) WLAN (which is expected to standardize the MU-MIMO transmission in WLANs) [24]. In particular, when the channel quality or the data length varies considerably between the receivers, MU-MIMO transmission may fail to utilize the available MIMO capacity to its full potential. A MAC protocol design that can switch between MU-MIMO and multiple SU-MIMO transmissions after taking into account the achievable performance could be one of the simple yet attractive solutions to address such issue. In this dissertation, by simply upgrading CSMA/CA, we present a MAC protocol that is capable of performing such switching task in a forthcoming VHT WLAN.

1.3 Organization of Dissertation

The remainder of this dissertation is organized as follows. Chapter 2 presents background information on WLANs and their standard, the networking protocol suite for WLANs, and the recent enhancements brought in by IEEE 802.11n amendment. In Chapter 3, performance analysis of SU-MIMO aware MAC protocol considering both PHY and

MAC enhancements is present. In Chapter 4, different modification approaches to upgrade existing MAC protocol into MU-MIMO aware MAC protocol are present. We also present detailed performance analysis of such MU-MIMO aware MAC protocols in this Chapter. Chapter 4 focuses on the downlink MU-MIMO transmission. Chapter 5 presents enhancement technique to adapt CSMA/CA for MU-MIMO reception in uplink. In Chapter 6, a MAC protocol to select efficient transmission mode between MU-MIMO and multiple SU-MIMO is present. Finally, Chapter 7 concludes the dissertation.

2 Wireless Local Area Networks

In this chapter, we provide brief overview of WLANs, WLANs protocol suite, and standardization activities in WLANs, including discussion on latest amendments in IEEE 802.11n, that will facilitate the understanding of contributions presented in this dissertation.

2.1 Overview of WLANs

WLANs are small area networks which have emerged as alternatives for the wired line networks such as Ethernet. WLANs allow wire-free networking in the local area network environment at a much lower cost using radio or infrared signals. Flexible network connectivity is the major benefit of WLANs over wired line network, where the network users are allowed to move around in a confined area while they are still connected to the network.

WLANs are standardized by IEEE 802.11 Working Group (WG). The WG creates a set of standards for WLAN to operate in the unlicensed portion of the Industrial, Scientific, and Medical (ISM) frequency band. There are series of IEEE 802.11 standards that have been produced since the formation of the WG in 1990. The popularly known amendments are IEEE 802.11 a, b, g, and n. Most of the commercial WLANs products available today are standardized with IEEE 802.11 standard and certified with *WiFi* (for interoperability between WLANs products from different vendors, *Wi-Fi Alliance* have created

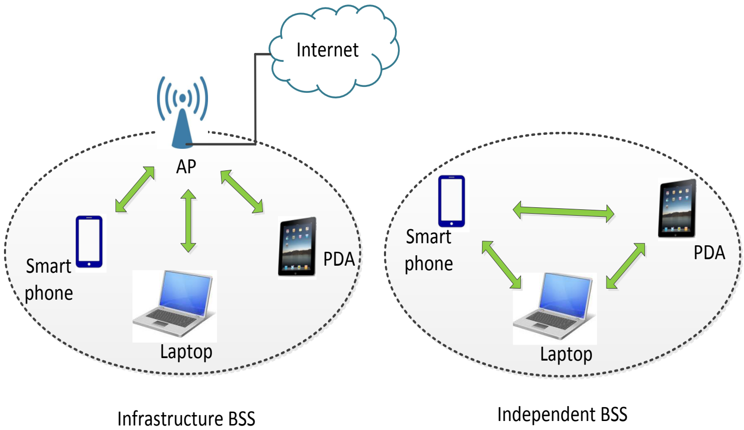


Figure 2.1: WLANs modes of operation: the *last hop* access network (left), and *ad hoc* network (right)

certification program) [25].

WLANs have two basic modes of operation. They are either used as a *last hop* connection to the Internet or as an stand-alone *ad hoc* network. Basically the network components are categorized into two types: APs and clients. APs are normally the routers, which act as base stations for clients. Clients can be other network devices such as laptops, smart phones, and PDAs. In *last hop* WLANs, client can either connect itself to Internet or to other clients via AP (as shown in Fig. 2.1 left), while in *ad hoc* WLANs, clients connect with each other independently (as shown in Fig. 2.1 right). In IEEE 802.11 terminology, the last hop topology is known as Infrastructure Basic Service Set (BSS) while AP-less *ad hoc* topology is known as Independent Basic Service Set (IBSS).

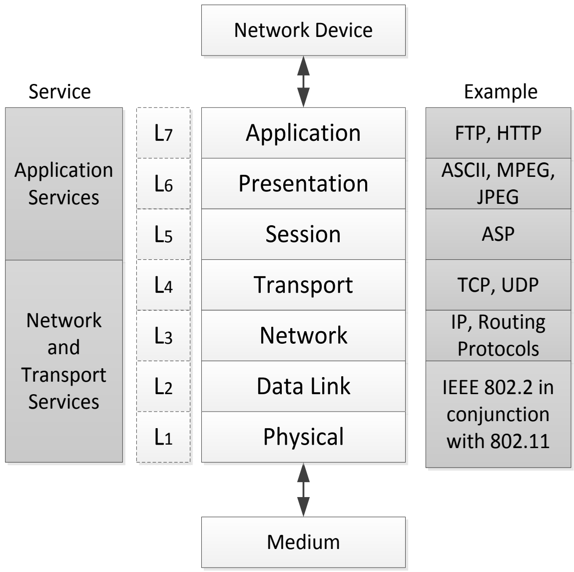


Figure 2.2: Layered architecture of the OSI reference model and some representative protocols at each layer

2.2 WLANs Protocol Suite

In general, networking protocol suite is a set of communication protocols that describe rules and procedures for exchanging data among the network entities in any communication system. The implementation of such protocol suite is also known as a protocol stack. These two terms are often used interchangeably.

The protocol stack for WLANs is based on Open System Interconnection(ISO/OSI) reference model developed by International Standard Organization (ISO) [26]. The reference model is an idealized model with seven different layers (L1-L7), as shown in Fig. 2.2. Each layer within a suite is responsible for a different facet of communications [27],[28]. The lowest protocol always deals with physical interaction of the hardware. Every higher layer adds more features. User applications usually deal with the topmost layer.

In networking point of view, among seven layers, the four lower layers (L1-L4) are responsible for establishing efficient communication path. In particular, L4 and L3 are responsible for end to end flow control and routing functionalities, respectively, while the L1 and L2 are responsible for establishing and managing the connection. The areas standardized by the IEEE 802.11 WG fall within the first and second layers of the networking protocol suite.

2.3 Standardization Activities in WLANs

In the course of development of WLANs, several different WLANs technologies and standards have come along, for example IEEE 802.11 standard and its variants, and High Performance Radio LAN (HiperLAN) defined by the European Telecommunications Standards Institute (ETSI) [29]. While the IEEE is an international organization, ETSI is a European alternative. But HiperLAN has so far not succeeded in the market and now the IEEE 802.11 and its variants are almost synonymous with the term WLANs.

IEEE 802.11 WG was formed in 1990, whose main role was to develop technical specifications for WLANs implementation. But it took until 1997 to get the original 802.11 standard. Since then, it has is-

Table 2.1: List of several variants of IEEE 802.11 standard

Series	**Date**	**Description**	**Remark**
802.11	1997	IEEE standard for WLAN MAC and PHY specifications	Initial standard
802.11a	1999	Higher Speed PHY extension in the 5 GHz band	54 Mbps, OFDM PHY
802.11b	1999	Higher Speed PHY extension in the 2.4 GHz band	11 Mbps, DSSS PHY
802.11g	2003	Further higher data rate extension in the 2.4 GHz	54 Mbps, OFDM PHY
802.11e	2005	MAC enhancements	Support for QoS
802.11n	2009	Enhancement for higher throughput	600 Mbps, MIMO PHY

sued several amendments to provide new services and capabilities for expanding wireless needs, and address shortcomings in former standard/s. Table 2.1 lists IEEE 802.11 standard and its variants that have already been approved and are currently in run.

IEEE 802.11 original standard has maximum data rate of 2 Mbps. It has included two forms of spread spectrum technique: Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS). Time Division Duplex (TDD) was provisioned for channel sharing between uplink and downlink. The modulation schemes specified were Differential Binary Phase Shift Keying (DBPSK) and Differential Quadrature Phase Shift Keying (DQPSK). Fundamentally, 802.11 had used CSMA/CA for its MAC protocol.

In year 1999, two PHY layer amendments were added to the original IEEE 802.11 standard, namely IEEE 802.11b and IEEE 802.11a. The IEEE 802.11b extended DSSS PHY to provide increased data rates up to 11 Mbps by using Complementary-Code Keying modulation scheme (CCK) [30]. While, on the other hand, IEEE 802.11a, defined PHY for 5.2 GHz supported 54 Mbps using a transmission technique known as Orthogonal Frequency-Division Multiplexing (OFDM)[31]. However, IEEE 802.11a amendment brought a compatibility problem with IEEE 802.11b. In addition, the use of 5.2 GHz carrier in Europe was generally restricted, making IEEE 802.11a popular only in North America [32]. To address those issues, in 2003, a new amendment known as IEEE 802.11g was introduced. It has similar PHY specification as that of IEEE 802.11a (use of OFDM, data rate up to 54 Mbps), but it operates over 2.4 GHz carrier.

In 2005, an amendment IEEE 802.11e was introduced. IEEE 802.11e was Quality of Service (QoS) extension of the former versions. Different new features in MAC layer are added by IEEE 802.11e. For example, service differentiation and prioritization [1] scheme, Transmission Opportunity (TXOP) sharing [2], and block acknowledgement.

In 2009, a high throughput WLAN standard, IEEE 802.11n, was

[1]Before that every service used to be considered as the best effort traffic but after its introduction high priority traffic like voice and video has a higher chance of being sent than a low priority traffic like e-mail and file sharing.

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

ratified which support up to 600 Mbps data rate. The support of hundreds of Mbps data rates has been achieved using several advanced communications and signal processing techniques. In particular, it introduced MIMO antenna system in PHY while on the MAC it supported enhanced MAC protocol features like frame aggregation, block acknowledgement, and bidirectional data flow.

2.4 Latest WLAN Standard: IEEE 802.11n

The IEEE 802.11n amendment is the latest addition for the IEEE 802.11 standard. The IEEE 802.11n standard enables a new class of consumer and enterprise products utilizing WLANs connectivity that is ten times faster than that is feasible with the former IEEE802.11a/b/g standards. To achieve the increased throughput, the IEEE 802.11n amendment describes enhancements to both PHY and MAC layers. In the following section, we summarize the key features brought in by IEEE 802.11n in WLANs PHY. Afterwards, the MAC enhancements are discussed.

2.4.1 IEEE 802.11n PHY

In IEEE 802.11n PHY, the newer throughput enhancing features introduced are MIMO spatial multiplexing, 40 MHz channelization, reduced guard interval, high rate coding, etc. Among them, introduction of MIMO systems is considered as the key innovation. In the following section, we emphasize the use of MIMO techniques in WLANs.

2.4.1.1 MIMO

MIMO is a form of smart antenna technology that uses multiple antenna elements. MIMO technology is being widely popular these days and is also being used in many new technologies such as IEEE 802.11 WLANs, IEEE 802.16 WMANs, LTE, etc. MIMO improves wireless channel capacity without additional bandwidth and power. The enhanced capacity may be in terms of improved link reliability or the increased spectral efficiency.

MIMO technology has been developed over many years. Before 1990s, multipath effect has long been considered as the main obstacle that prevents high throughput transmission in wireless networks; especially due to fading. However, introduction of MIMO system brought a new revolution in wireless communication and provided a new way to utilize the so called obstacle (multipath) into benefits. By employing multiple antenna elements and some advanced Digital Signal Processing (DSP) techniques, MIMO can facilitate the system to set up multiple data links on the same time and frequency domain. And, by exploiting the multiple data links created in MIMO, the multiple data stream could be transmitted simultaneously. Different transmission modes or the antenna configuration formats could be selected in this purpose, such as,

SISO:	Single Input Single Output
SIMO:	Single Input Multiple output
MISO:	Multiple Input Single Output
MIMO:	Multiple Input multiple Output

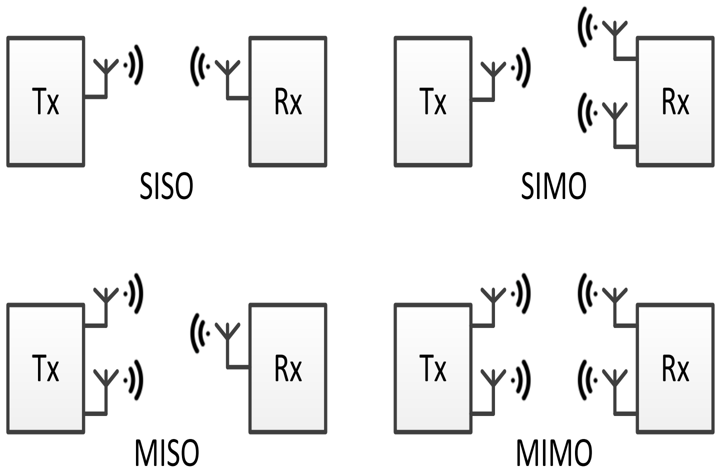


Figure 2.3: MIMO antenna configuration

Schematically antenna configuration formats have been shown in Fig. 2.3. Again, if we consider MIMO communication, then there could be two types of transmission: transmission of the same data stream from multiple antenna elements (spatial diversity) and transmission of different data stream from each antenna element (spatial multiplexing).

- Spatial diversity: Spatial diversity, also commonly referred to as the space diversity, is a MIMO transmission technique that uses two or more than two antenna elements to transmit the same data stream. By employing the multiple antenna elements, spatial diversity takes advantage of the different radio paths that occurs due to multipath. Spatial diversity improves the quality and the reliability of the wireless channel. The multiple antenna receiver receives several observations of the same signal and collectively provides a robust link.

- Spatial multiplexing: Spatial multiplexing, also often referred to as the space division multiplexing, is a MIMO transmission technique that transmits separate and independent data streams concurrently from each antenna elements in the same time and frequency domain. Spatial multiplexing improves the spectral efficiency of the wireless channel. Spatial multiplexing provides additional data capacity by utilizing the different paths to carry additional traffic. The space dimension is reused in spatial multiplexing.

2.4.1.2 SU-MIMO

IEEE 802.11n has supported both the spatial multiplexing and the spatial diversity based MIMO transmission schemes. None of these schemes are mandatory, however, optional. The current standard specifies that up to 4 spatial streams can be transmitted employing either of them.

IEEE 802.11n has also defined three types of transmission modes and has brought changes on the Physical Layer Convergence Protocol

(PLCP) header to indicate them. High Throughput (HT) transmission, HT mixed mode transmission, and non-HT mode transmission are the respective transmission modes. HT transmission corresponds to MIMO to MIMO transmission. In this transmission mode, compatibility with legacy SISO clients is not necessary. Whereas, mixed mode transmission corresponds to MIMO to SISO transmission, or vice versa. Mixed mode transmission gives full support for the legacy clients. On the other hand, non-HT mode transmission is a legacy SISO to SISO transmission.

IEEE 802.11n has supported the MIMO communication between only one set of transmitter-receiver pair, which is often called SU-MIMO communication. In the following section, we present the detail system model of this scheme.

2.4.1.3 SU-MIMO System Model

In wireless communication, the wireless channel is modeled as,

$$y = hx + n. \tag{2.1}$$

Where, x is the input signal, h is the channel response, y is the output signal, and n is the channel noise. n is a zero mean complex Gaussian random variable with variance σ^2. Thus, the channel Signal-to-Noise-

Ratio (SNR) can be expressed as,

$$SNR = \frac{E|hx|^2}{E|n|^2} = \frac{E|x|^2}{E|n|^2}|h|^2 = \frac{Es}{\sigma^2}|h|^2. \tag{2.2}$$

Due to channel noise, the error could be added in the received signal. If we assume maximum likelihood receiver is used to decode the received signal when there is channel response h, the error probability that the received signal y is different than the transmitted signal x ($Pr\{\varepsilon|h|\} = Pr\{y \neq x\}$) satisfies,

$$Pr\{\varepsilon|h\} \leq \left\{-\frac{\frac{Es}{\sigma^2}|h|^2}{2}\right\}. \tag{2.3}$$

The above presented relation represents the error probability for a given realization of the channel response h. However, to obtain entire error probability, we must average the conditioned error probability with respect to $|h|^2$. Thus, on averaging with respect to *Rayleigh* fading channel, as in [33], we get,

$$Pr\{\varepsilon\} \leq \frac{1}{\left(1 + \frac{Es}{2\sigma^2}\right)}. \tag{2.4}$$

Now let us consider the SU-MIMO channel with M number of transmit antenna elements and N number of receive antenna elements, $M \times N$ MIMO system as shown in Fig. 2.4. The received signal at any

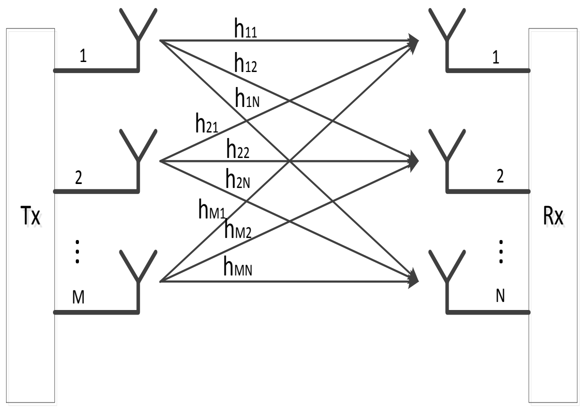


Figure 2.4: $M \times N$ MIMO system

arbitrary antenna, let say i, can be expressed as,

$$y_i = \sum_{j=1}^{M} h_{ij} x_j + n_i, \qquad i = 1, 2, ..., N. \tag{2.5}$$

Where, h_{ij} is the channel response of the link j transmit antenna to i receive antenna. The overall $M \times N$ MIMO system can be modeled as,

$$y = Hx + n. \tag{2.6}$$

Where,

$$y = \begin{bmatrix} y_1 \\ y_2 \\ . \\ y_N \end{bmatrix}, \qquad x = \begin{bmatrix} x_1 \\ x_2 \\ . \\ x_M \end{bmatrix}, \qquad n = \begin{bmatrix} n_1 \\ n_2 \\ . \\ n_N \end{bmatrix}. \tag{2.7}$$

$$H = \begin{bmatrix} h_{11} & h_{12} & . & . & . & h_{1M} \\ h_{21} & h_{22} & . & . & . & h_{2M} \\ . & . & . & . & . & . \\ h_{N1} & h_{N2} & . & . & . & h_{NM} \end{bmatrix}. \tag{2.8}$$

If we consider spatial diversity based transmission, from (1.4) we can easily formulate the error probability for the transmitted signal and can be expressed as,

$$Pr\{\varepsilon\} \leq \frac{1}{\left(1 + \frac{Es}{2min\{M,N\}\sigma^2}\right)^{MN}}. \tag{2.9}$$

The above expressed relation shows that if we apply MIMO spatial diversity, we can get the diversity gain in the order of MN. However, note that above relation is for the full diversity case only, i.e. when there is both transmit and receive diversity in the system. During MISO or SIMO the diversity order will be different and will be only in the order of M and N, respectively.

Similarly, we can also express the spatial multiplexing gain for the SU-MIMO channel. Since all the received signals are available at the receiver for processing, it can be assumed that receiver can easily determine the channel transfer matrix. When the channel transfer matrix is known, the transmitted data streams can be reconstructed by multiplying the received vector with the inverse of the transfer matrix. The input signal x is linearly transformed by the channel H and appended with noise n resulting in the output y. Given H (generally a channel estimation procedure precedes the real data exchange to get the channel H) and disregarding n, the transmitted symbol vector x can be retrieved from the received signal vector y by $x = H^{-1}y$. Therefore,

$$Multiplexing\ gain = \frac{C_{MIMO}}{C_{SISO}} = min\{M, N\}. \tag{2.10}$$

2.4.2 IEEE 802.11n MAC

The IEEE 802.11n modifications to the MAC include the modification of CSMA/CA into SU-MIMO aware MAC protocol, addition of frame aggregation (i.e., sending multiple MAC frames in one PHY layer packet to reduce overhead), BACK enhancement (acknowledging frames in blocks, also to reduce overhead), and bi-directional data flow protocol (allows the transmit station currently holding the channel to efficiently transfer control to its receiver, without the need for later to initiate a whole data transfer process). In what follows, we describe

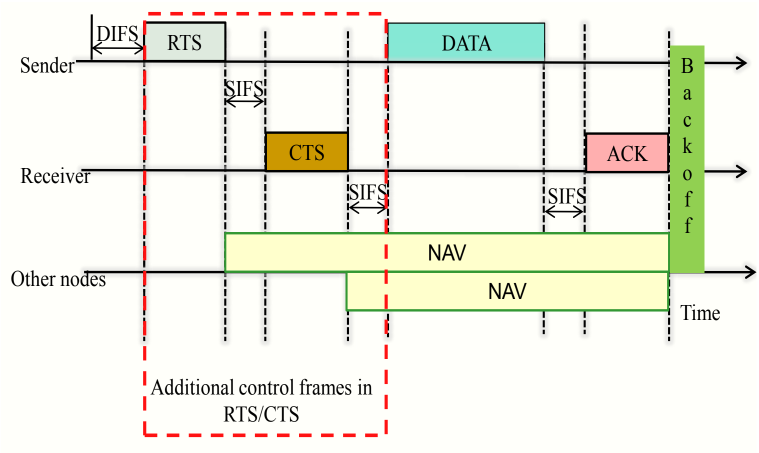


Figure 2.5: CSMA/CA MAC

them in detail.

2.4.2.1 SU-MIMO aware MAC Protocol

The IEEE 802.11 MAC supports shared access to the wireless medium through a technique called CSMA/CA. In CSMA/CA MAC protocol, as shown in Fig. 2.5, a node with a packet to send first monitors the channel activity. If the channel is found to be idle for an interval that exceeds the Distributed InterFrame Space (DIFS), the node continues its transmission. Otherwise, the node waits until the channel becomes idle for DIFS period and then computes a random backoff time for which it will defer its transmission. The defer time is a product of the selected backoff value and a slot duration. After the medium becomes idle for a DIFS period, nodes decrement their backoff timer until the channel becomes busy again or the timer reaches zero. If the timer

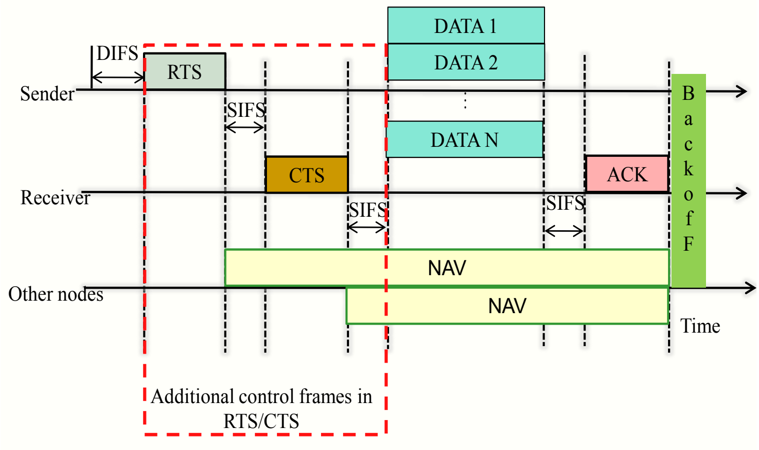


Figure 2.6: SU-MIMO aware MAC

has not reached zero and the medium becomes busy, the node freezes its timer. When the timer is finally decremented to zero, the node transmits its packet. If two or more nodes decrement to zero at the same time, a collision occurs.

In CSMA/CA RTS/CTS access mechanism, when a node monitors the channel activity and finds it idle for more than the DIFS, node sends a special reservation packet called RTS and the intended receiving node will respond with CTS after Short InterFrame Space (SIFS). Other nodes which overhear RTS and CTS update their Network Allocation Vector (NAV[3]) accordingly. The transmitting node is allowed to transmit its packet only if the CTS packet is received correctly.

SU-MIMO aware MAC is an extended version of the CSMA/CA mechanism, as shown in Fig. 2.6. The main extensions are in the frame

[3]NAV is intended for the virtual carrier sensing.

control fields and in the control packets format. The control frames are wrapped in the control wrapper frame, which includes information about the ongoing modes of transmission. For channel estimation, the training fields[4] are included in PLCP. Two types of training fields are used in IEEE 802.11n. The short training field is used for automatic gain control and time synchronization. Whereas, long training field is used for channel estimation. The number of long training field is equal to the number of data streams multiplexed by the transmitter.

2.4.2.2 Frame Aggregation

A second major breakthrough of IEEE 802.11n is the introduction of frame aggregation. IEEE 802.11n has provisioned two standard types of aggregation schemes: Aggregate MAC Service Data Unit (A-MSDU) and Aggregate MAC Protocol Data Unit (A-MPDU). In A-MSDU scheme, two or more than two MSDUs are aggregated to form a MPDU. Each A-MSDU consists of several subframes each with a separate MSDU. However, a final MPDU size is limited to 7955 bytes at maximum. Each subframe also consists of the subframe header and padding bits. Subframe header contains destination address, source address, and the MSDU length information. The size of the MSDUs can vary but none of them can be greater than 2304 bytes. Padding bits are included to make the subframe a multiple of 4 bytes. The

[4]A training field is a fixed symbol specified in the standard and is known both at the transmitter and receiver.

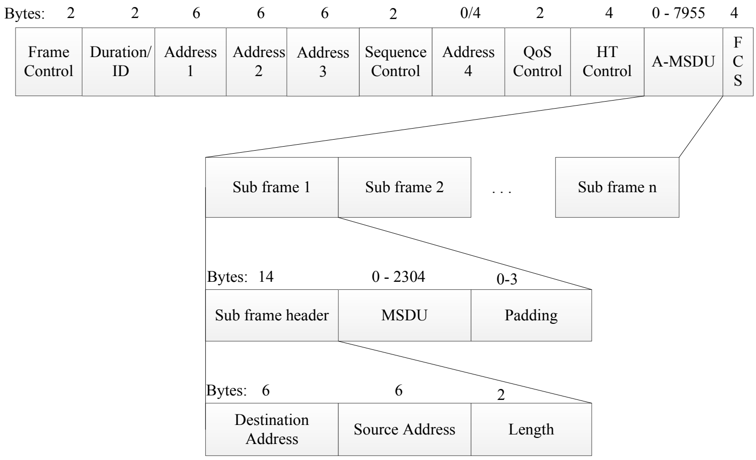


Figure 2.7: Standard frame format for A-MSDU

standard frame format for A-MSDU is shown schematically in Fig. 2.7. Since all the subframes share a common MAC header and Frame Check Sequence (FCS) in this scheme, it is impossible to re-transmit the particular subframe in case of its corruption.

In A-MPDU scheme, two or more than two MPDUs with common PHY header are aggregated. Every A-MPDU consists of several subframes each with a separate MPDU. However, A-MPDU length should not exceed 64 KBytes at maximum. Each subframe also consists of the delimiter and the padding bits. Delimiter contains 4 reserved bits, a MPDU length information, Cyclic Redundancy Check (CRC), and unique pattern of 8 bits. Bits in unique pattern are used for finding out the next delimiter with minimal computation in case of a delimiter corruption [34]. MPDU in a subframe contains individual MAC header, MSDU, and FCS. The standard frame format for A-MPDU is

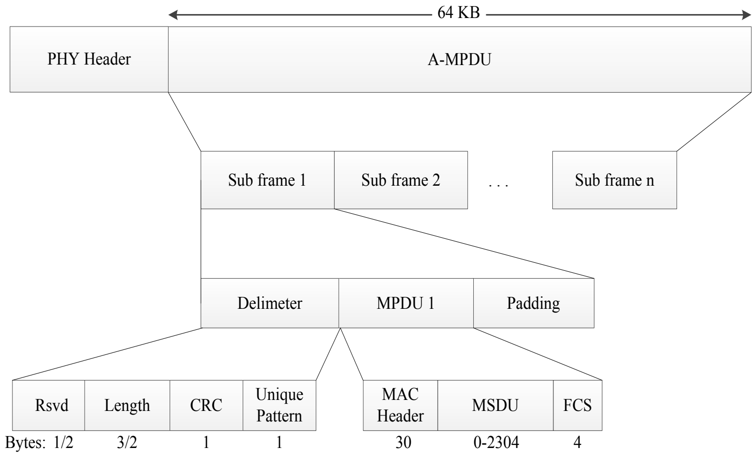


Figure 2.8: Standard frame format for A-MPDU

shown schematically in Fig. 2.8. Since all the subframes consists individual MAC header and FCS in this scheme, retransmission of selected subframe is possible in case of corruption.

2.4.2.3 Block Acknowledgement

In BACK scheme, instead of transmitting individual ACK frames for each received frames in an aggregated frame, ACKs for all received frames are concatenated into a single frame and then sent in one attempt. It is a bitmap based acknowledging scheme where each bit sequence represents the status of each frame inside the aggregated frame. IEEE 802.11n has mandatorily defined this feature to be included during HT transmission.

2.4.2.4 Bi-directional Data Flow

Bi-directional data flow, also referred as reverse data flow, is a scheme that gives an opportunity for a receiver to transmit the data ready to be sent to the transmitter after receiving its intended data from transmitter on the transmitter's initiated TXOP in the same channel. To facilitate this technique advanced negotiation is required in prior during association process, so that the entire transmission duration is known by other nodes. This scheme aids especially to the data traffic having bi-directional nature like VoIP and video teleconferencing. Advantages like overhead and delay reduction can be enjoyed with this scheme.

2.4.3 Limitation of IEEE 802.11n

Two types of spatial multiplexing could be supported with MIMO systems: SU-MIMO and MU-MIMO. As mentioned earlier, SU-MIMO is a point-to-point MIMO communication, whereas, MU-MIMO is a point-to-multipoint MIMO communication (or vice versa). IEEE 802.11n has only supported SU-MIMO. But, as explained earlier, due to various network characteristics, SU-MIMO is not always applicable. In order to address limitations of SU-MIMO, recently the use of MU-MIMO has been recommended. But realizing the advantages of MU-MIMO in existing WLANs requires significant changes in the MAC protocol. The underlying MAC protocol must be upgraded to MU-MIMO aware

MAC protocol.

2.4.3.1 MU-MIMO aware MAC Protocol

MU-MIMO aware MAC protocol can be viewed as a MAC protocol that allows a concurrent transmission to or from multiple users in the same transmission cycle. As SU-MIMO is point-to-point MIMO communication, in general, it can be conceived that SU-MIMO aware MAC follows same channel access mechanism as that of legacy CSMA/CA with exchange of slightly modified control packets only. But the same does not apply for MU-MIMO. As MU-MIMO is point-to-multipoint MIMO communication, it needs to exchange higher number of the extended control packets during negotiation with multiple receivers. More importantly, modification in conventional CSMA/CA is required to accomplish Channel State Information (CSI) of all the intended receivers at the transmitter side such that the transmitter can know about interference situation of its receivers and apply interference limited precoding, also known as interference limited data preprocessing, prior to data transmission to facilitate co-users interference cancelation at receiver side.

3 Performance Analysis of SU-MIMO aware MAC Protocol

In this chapter, we present achievable performance analysis of SU-MIMO aware MAC protocol in IEEE 802.11n WLAN. We consider MIMO spatial multiplexing in PHY and the enhanced MAC features, frame aggregation, bi-directional data flow, and block acknowledgement, in MAC layer.

3.1 Motivation

IEEE 802.11n has brought different modifications to the PHY and MAC layer specifications of the original IEEE 802.11 standard to address the ever increasing demand of the higher throughput. It not only has introduced MIMO technology at the PHY layer, but also various features like frame aggregation, bi-directional data flow, and BACK at the MAC layer. To support SU-MIMO communication, the IEEE 802.11n has upgraded the conventional CSMA/CA MAC protocol into SU-MIMO aware MAC protocol. The adoption of MIMO technology in the PHY layer boosts up the raw channel rate while the enhanced MAC features mitigate the transmission overheads. Various analytical and empirical studies have attempted to characterize the effects of such PHY and MAC enhancements in overall performance of the network. To supplement those studies, in this chapter, we present the bounding (maximum achievable) performance of such enhancements considering throughput and delay performance measures.

3.2 Introduction

To satisfy high data rate demand of emerging services including multimedia streaming and video teleconferencing in WLANs, the latest release of IEEE 802.11n amendment has introduced major modifications to both the PHY and MAC layer specifications. In PHY layer, it has introduced MIMO technology, while various MAC enhancement features including frame aggregation, BACK, and bi-directional data flow are introduced in the MAC layer.

Even though the implementation of MIMO technology can boost up the PHY capacity, it cannot contribute much in enhancing MAC layer capacity due to some inherent problems of the CSMA/CA based MAC protocol specified in IEEE 802.11. In particular, its throughput and delay performance are bounded regardless of increase in the PHY channel rate. Such bounded performance is due to the fixed channel overheads associated with random backoff, various IFSs, and the provision of issuing control packets at the basic (lower) rate [35]. Hence, IEEE 802.11n introduced the following techniques to reduce those overheads: frame aggregation, block acknowledgement, and bi-directional data flow. Frame aggregation technique combines two or more frames and transmit the combined frame as a single frame [36]. Thus, it significantly reduces channel access overheads (backoff and IFSs) and transmission overheads (transmission of PHY and MAC headers). BACK is a technique to reduce overhead in terms of transmission of acknowledgement packets. In this technique, a single block ACK is sent for the aggregated frames instead of acknowledging them individually [37]. On the other hand, bi-directional data flow technique is intended to reduce the channel access overhead for bidirectional traffic. In this technique, transmitter sends its data first in forward link and then receiver sends its packet to reverse link utilizing the TXOP of transmitter [38]. Different analytical and simulation based studies have been carried to analyze the effect of aforesaid PHY and MAC enhancement techniques [39]-[41]. Nevertheless, there has been no work in quantifying the bounding (maximum achievable) performance enhancement due to such features. Therefore, in this chapter we present the bounding performance analysis considering the throughput and delay performance measures.

3.3 Numerical Analysis

Achievable performance of a system is the performance that the system can deliver on the best case scenario. In order to emulate the best case scenario in IEEE 802.11n WLAN, we abide by the following assumptions: (a) in each transmission cycle, there is only one active transmitter-receiver pair, (b) transmitter-receiver pair always has packets to send, (c) channel is error free, and (d) spatial multiplexing and bi-directional data flow are supported.

In unidirectional data flow with CSMA/CA based channel access mechanism, as shown in Fig. 3.1, a node with data to send first monitors the channel activity. If the channel is found to be idle for DIFS, the node continues its transmission. Otherwise, it waits until the channel becomes idle for the DIFS period and then computes a random back-off time for which it will defer its transmission. After the medium becomes idle for a DIFS period, nodes decrement 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 its timer. When the timer is finally decremented to zero, the node transmits RTS and the intended receiving node will respond with CTS packet after SIFS. Other nodes which overhear RTS and CTS update their NAV. After SIFS time interval, transmitting node sends the concurrent data streams. Finally, after another SIFS time interval, receiver node acknowledges the reception via BACK.

On the other hand, in case of bi-directional data flow, as shown in Fig. 3.2, the receiver node after receiving data streams from transmitter, let say Forwarded Data streams (F-DATA), acknowledges the reception with BACK for Forwarded Data (F-BACK) and then sends back the Reverse Data streams (R-DATA) to the transmitter in the same link. Which is then acknowledges by BACK for Reverse Data (R-BACK) after SIFS.

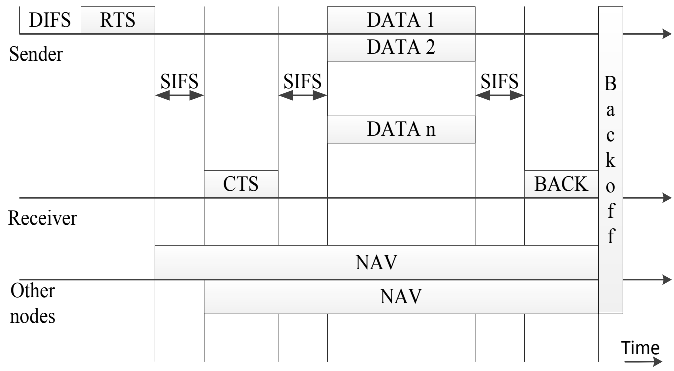


Figure 3.1: Channel access mechanism for unidirectional data flow

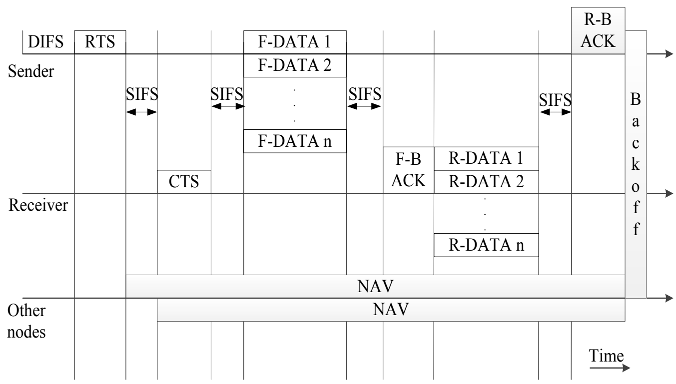


Figure 3.2: Channel access mechanism for bi-directional data flow

3.3.1 Maximum Achievable Throughput

Throughput can be defined as the rate of successful transmission of data packets in the channel. Thus, maximum achievable throughput, S^{max}, for IEEE 802.11n with the $M \times N$ antenna configuration can be expressed as,

$$S^{max} = \frac{\sum_{j=1}^{z} E[P]}{T_s}. \tag{3.1}$$

Here $z = min\{M, N\}$, $E[P]$ is the payload size in bits, and T_s is the time for successfully transmitting those bits. T_s when implementing A-MSDU and A-MPDU aggregation schemes and during unidirectional and bi-directional data flows, $T_{s,\ A-MSDU}^{Uni}$, $T_{s,\ A-MSDU}^{Bi}$ $T_{s,\ A-MPDU}^{Uni}$, and $T_{s,\ A-MPDU}^{Bi}$, are different with each other because of the differences in channel access mechanisms, as shown in Fig.3.1 and Fig. 3.2, respectively. The differences are also because of the difference in their frame formats. T_s for each of the cases can be expressed as follows.

$$\begin{aligned} T_{s,\ A-MSDU}^{Uni} &= \overline{W} \times \sigma + T_{DIFS} + T_{RTS} + 3T_{SIFS} \\ &+ T_{CTS} + T_{PHY_{HDR}} + T_{MAC_{HDR}} \\ &+ T_{A-MSDU} + T_{FCS} + T_{B-ACK}, \end{aligned} \tag{3.2}$$

$$\begin{aligned} T_{s,\ A-MSDU}^{Bi} &= \overline{W} \times \sigma + T_{DIFS} + T_{RTS} + 4T_{SIFS} \\ &+ T_{CTS} + 2T_{PHY_{HDR}} + 2T_{MAC_{HDR}} \\ &+ 2T_{A-MSDU} + 2T_{FCS} + 2T_{B-ACK}, \end{aligned} \tag{3.3}$$

$$
\begin{aligned}
T^{Uni}_{s,\ A-MPDU} &= \overline{W} \times \sigma + T_{DIFS} + T_{RTS} + 3T_{SIFS} \\
&+ T_{CTS} + T_{PHY_{HDR}} + T_{A-MPDU} \\
&+ T_{B-ACK},
\end{aligned} \tag{3.4}
$$

$$
\begin{aligned}
T^{Bi}_{s,\ A-MPDU} &= \overline{W} \times \sigma + T_{DIFS} + T_{RTS} + 4T_{SIFS} \\
&+ T_{CTS} + 2T_{PHY_{HDR}} + 2T_{A-MPDU} \\
&+ 2T_{B-ACK}.
\end{aligned} \tag{3.5}
$$

Where, $\overline{W}$ is an average backoff value, σ is the slot time, and $T_{(.)}$ indicates the total time required for sending respective frames. If we suppose k number of MSDUs are concatenated to form the A-MSDU or the A-MPDU then the time required for transmitting such A-MSDU and A-MPDU, T_{A-MSDU} and T_{A-MPDU}, can be expressed as follows

$$
\begin{aligned}
T_{A-MSDU} &= k \times (T_{Sub\ frame\ header} \\
&+ T_{MSDU} + T_{Padding}),
\end{aligned} \tag{3.6}
$$

$$
\begin{aligned}
T_{A-MPDU} &= k \times (T_{Delimeter} + T_{MAC_{HDR}} \\
&+ T_{MSDU} + T_{FCS} + T_{padding}).
\end{aligned} \tag{3.7}
$$

By replacing T_s in (3.1) with $T^{Uni}_{s,\ A-MSDU}$, $T^{Bi}_{s,\ A-MSDU}$, $T^{Uni}_{s,\ A-MPDU}$, and $T^{Bi}_{s,\ A-MPDU}$, maximum achievable throughput for each transmission case can be obtained.

3.3.2 Minimum Achievable Delay

Access delay can be defined as the time interval from a moment the node is ready to access the medium to a moment the transmission finishes successfully. Thus, the achievable minimum delay for the IEEE 802.11n when employing spatial multiplexing during A-MSDU and A-MPDU aggregation schemes with unidirectional and bi-directional data flows, $D^{Uni}_{min,\ A-MSDU}$, $D^{Bi}_{min,\ A-MSDU}$, $D^{Uni}_{min,\ A-MPDU}$, and $D^{Bi}_{min,\ A-MPDU}$, can be expressed as follows.

$$\begin{aligned} D^{Uni}_{min,\ A-MSDU} &= \overline{W} \times \sigma + T_{DIFS} + T_{RTS} + 2T_{SIFS} \\ &+ T_{CTS} + T_{PHY_{HDR}} + T_{MAC_{HDR}} \\ &+ T_{A-MSDU} + T_{FCS}, \end{aligned} \tag{3.8}$$

$$\begin{aligned} D^{Bi}_{min,\ A-MSDU} &= \overline{W} \times \sigma + T_{DIFS} + T_{RTS} + 3T_{SIFS} \\ &+ T_{CTS} + 2T_{PHY_{HDR}} + 2T_{MAC_{HDR}} \\ &+ 2T_{A-MSDU} + 2T_{FCS}, \end{aligned} \tag{3.9}$$

$$\begin{aligned} D^{Uni}_{min,\ A-MPDU} &= \overline{W} \times \sigma + T_{DIFS} + T_{RTS} + 2T_{SIFS} \\ &+ T_{CTS} + T_{PHY_{HDR}} + T_{A-MPDU}, \end{aligned} \tag{3.10}$$

$$D^{Bi}_{min,\ A-MPDU} = \overline{W} \times \sigma + T_{DIFS} + T_{RTS} + 3T_{SIFS} + T_{CTS} + 2T_{PHY_{HDR}} + 2T_{A-MPDU}. \quad (3.11)$$

3.4 Performance Evaluation and Discussion

We evaluate performance numerically based on the above presented mathematical expressions taking into consideration the parameters presented in Table 3.1. The selected parameters are for mixed mode transmission. These parameters have been adopted in such a way that they could insure the interoperability between IEEE 802.11n and IEEE 802.11g WLANs. The MSDU size is fixed to 1500 bytes. We consider different configurations. Taking into account the aggregation, BACK, and bi-directional data flow schemes, performance is evaluated for different network conditions where channel Data Rate (DR) ranges from 6 Mbps to 144 Mbps.

Table 3.1: System parameters considered for performance analysis of SU-MIMO aware MAC

Parameters	**Value**
MAC header	256 bits
PHY header	40 μs
RTS packet	208 bits
CTS packet	160 bits
ACK packet	160 bits
DIFS	50μs
SIFS	10μs
Slot time	20μs
Basic data rate	6 Mbps
Minimum contention window (W)	16

Maximum achievable throughput and minimum achievable delay with different A-MSDU set up is presented in Fig. 3.3 for unidirectional and bi-directional data flow, respectively. It can be observed that in these results throughput linearly increases with the number of antenna elements but not with DR. For example, if we consider the performance for unidirectional A-MSDU with 5 aggregated MSDUs, throughput for DR 54 Mbps has increased from 33.7 Mbps to 67.5 Mbps and again it has increased from that 67.5 Mbps to 135 Mbps on doubling the spatial streams, respectively. However, if we observe the throughput for DR 54 Mbps and DR 144 Mbps for 4x4 transmission cases in unidirectional A-MSDU, throughput has increased from 135 Mbps to 224 Mbps only, i.e. on increasing the data rate by 2.66 times, throughput increases by 1.65 times only. Relatively similar trend on performance can be observed on rest of the configurations as well. Likewise, if we observe the results for performance in unidirectional data flow and bi-directional data flow, it can be noticed that although the throughput has increased comparatively in bi-directional case it has not increased highly or in other words it has increased by far less than two folds. For example, if we observe the results in unidirectional A-MSDU and bi-directional A-MSDU with 5 aggregated MSDUs, the throughput for DR 54 Mbps during 4x4 transmission has increased from 135 Mbps to 159 Mbps only. In case of minimum achievable delay performance, it can be remarked that delay is independent of antenna elements variation. However, in these results too, it can be observed that delay has no linear relationship with DR (delay does not decrease linearly with rise in DR). For example, delay in unidirectional A-MSDU with 5 aggregated MSDUs for DR 54 Mbps has been decreased from 1.7 ms to 1 ms only for DR 144 Mbps, i.e. on increasing the data rate by 2.66 times, delay has been decreased only by 0.59 times. While, in unidirectional A-MSDU and bi-directional A-MSDU, delay has increased from 1.7 ms to 2.92 ms, i.e. by more than 1.7 times.

Similarly, on the base of A-MSDU performance, we can visualize the performance of A-MPDU aggregation as well. Since they follow the similar trend on aggregation, i.e. aggregating different MSDUs, the results are also of similar trend. However, due to the requirement of transmission of individual MAC header and few of the additional control bits with each aggregated MSDUs, the throughput slightly decreases and delay slightly increases in A-MPDU. For example, we observed that in unidirectional A-MSDU and A-MPDU with 5 aggregated MSDUs and 5 aggregated MPDUs (both consisting 5 MSDUs) for 4x4 transmission with DR 144 Mbps, throughput decreased from 224 Mbps to 221 Mbps and delay increased by 1%. Nevertheless, it is noteworthy that these two schemes are entirely different schemes and they are independently adopted based on network requirements and network conditions. From the presented results it can be reasoned out that no linear throughput-delay gain can be achieved by increasing DR. Similarly, bi-directional data flow even cannot leverage linear throughput enhancement. In addition, it can also be observed

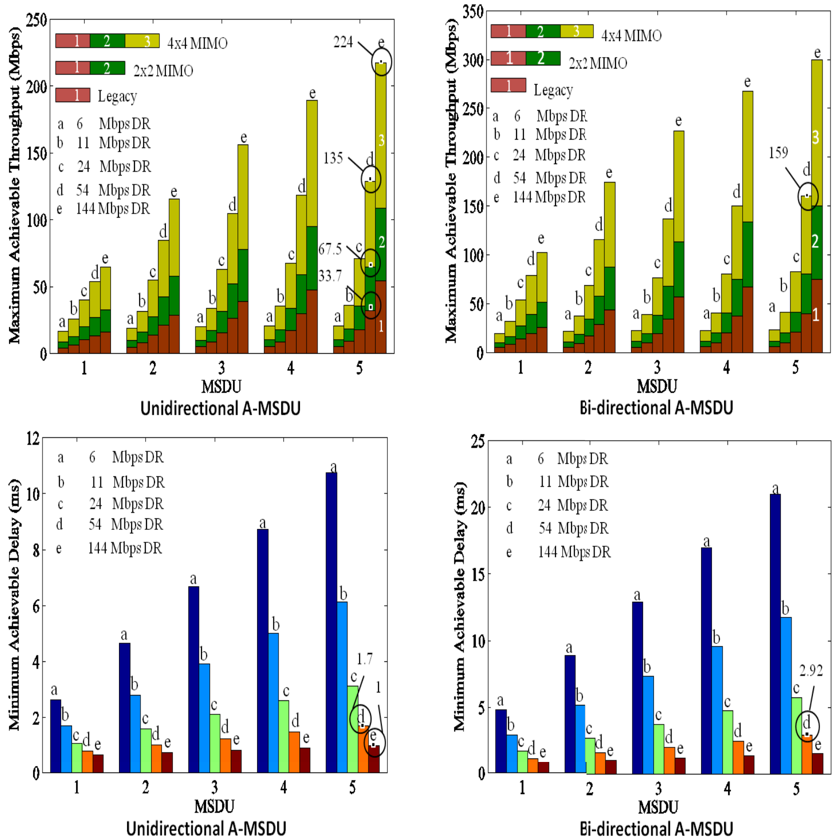


Figure 3.3: Maximum achievable throughput and minimum achievable delay for IEEE 802.11n WLAN during A-MSDU aggregation with unidirectional and bi-directional data flow

that when employing lower DR, throughput and delay gain has always been suppressed. Thus, care should be taken when adapting spatial multiplexing or spatial diversity. By implementing spatial multiplexing linearly enhanced throughput can be achieved. However, spatial multiplexing cannot be implemented in higher DR; as logical channels cannot be treated as robust link channel in every case. On the other hand, spatial diversity can help to transmit the data in higher DR but we may need to sacrifice the throughput that could be obtained from independent logical channels. Hence, there always remains trade-off between them and DR, and needs to be optimized carefully. Similarly, employing MAC enhancing features can considerably enhance the performance but it cannot always act as it is expected. For example, larger aggregated frames increase delay. For real time, delay sensitive, and short packet length applications, it can be problematic. Furthermore, unless there are enough packets to send in the queue, it is not worth applying aggregation. Thus, there is a tradeoff between throughput and delay for frame aggregation always. Hence, care should also be taken when adopting them. Apart from these issues, since discussed results are only for maximum achievable performance, probability of collision during packets transmission and the probability of error in the transmitted bit also play vital role in the systems performance. Thus detail performance analysis considering all the enhancement features along with collision probability and error probability inclusion is also of the essence, and will be covered in the future study.

3.5 Concluding Remarks

In this chapter, we analyzed the bounding performance of SU-MIMO aware MAC in IEEE 802.11n considering various PHY and MAC layer enhancements. For that we derived the expressions for the performance matrices like maximum achievable throughput and the minimum achievable delay for different cases of unidirectional and bidirectional flow of traffics considering BACK and various aggregation schemes. The presented analysis is helpful to understand tradeoff among the performance of different schemes.

4 Performance Analysis of MU-MIMO aware MAC Protocols

In this chapter, we present performance analysis of MU-MIMO aware MAC protocols. We investigate different modification approaches that upgrade WLANs default MAC protocol CSMA/CA into MU-MIMO aware CSMA/CA and then present their detailed performance analysis.

4.1 Motivation

To realize MU-MIMO advantages over WLANs, it requires significant changes in the MAC protocol. Either the dominant MAC protocol CSMA/CA needs to be replaced by a novel MU-MIMO aware MAC protocol or it should be upgraded into MU-MIMO aware CSMA/CA. Nevertheless, the simplest approach would be upgrading CSMA/CA. Simple modifications in control packets format and/or channel access mechanism can upgrade CSMA/CA into simple, yet practicable, MU-MIMO aware MAC protocol. By utilizing convenient changes, several modification approaches can be provisioned for this purpose. Hence, it becomes important to understand their performance benefits and trade-offs. In this chapter, we discuss some of such modification approaches that best represent the possible modifications. Based on analytical modeling, we provide their detailed performance analysis in terms of throughput and delay. We also derive expressions for achievable performance analysis and present their performance limits.

4.2 Introduction

An appropriately modified control packets exchange provisioned with an adequately carried out channel access mechanism based on CSMA/CA RTS/CTS access scheme can upgrade CSMA/CA into MIMO aware MAC protocol. Some of the prior researches [42]-[45] advised such modifications and demonstrated enhanced performance too. With proper modification handling, both the SU-MIMO and MU-MIMO can be supported with MIMO aware CSMA/CA.

As SU-MIMO is point-to-point MIMO communication, in general, it can be conceived that SU-MIMO aware CSMA/CA follows same channel access mechanism as that of legacy CSMA/CA with exchange of slightly modified control packets only. Thus, it can be envisioned that throughput increases approximately in the same fold according to the number of antenna elements in use; leaving the delay constant. But the same does not apply for MU-MIMO. As MU-MIMO is point-to-multipoint MIMO communication, it needs to exchange higher number of the extended control packets during negotiation with multiple receivers. If control packets are transmitted serially, one after one, to avoid risk of control packets corruption and to save cost and complexity from signal processing[1], it leads to heavy overhead in time and ultimately decreases the network performance. If control packets are transmitted simultaneously to decrease overhead's effect, it leads

[1]To decode simultaneously transmitted signals, it demands high computational complexity with sophisticated hardware-filters.

to higher cost and complexity in signal processing and may also increase the risk of control packets corruption. Hence, MU-MIMO fails to give similar performance to that of SU-MIMO while maintaining the same level of network cost and complexity. Nevertheless, a noteworthy point is that, though SU-MIMO seems to be desirable it is not always applicable. Due to various network characteristics like variable channel load, constraint of backward compatibility, and delay sensitivity, SU-MIMO cannot always leverage linearly enhanced performance. Similarly, PHY characteristics like channel rank loss and antenna correlation effects also play an adverse role in SU-MIMO performance [46]. Hence, in many cases SU-MIMO can prevent from fully utilizing the available MIMO capacity. In such scenarios, MU-MIMO would be preferable. However, in spite of its high practical importance, MU-MIMO has not been standardized yet in WLANs standard. While SU-MIMO has already been standardized by IEEE 802.11n.

IEEE 802.11n has also provisioned modified CSMA/CA as its MIMO aware MAC protocol. As stated earlier, a control frame called control wrapper frame has been defined for this purpose such that the control packets are wrapped within the control wrapper frame and then exchanged between the transmitter and receiver [47]. On the other hand, as few of the unresolved matters related to MAC layer issues are still under consideration, MU-MIMO is yet to be standardized. For instance, issues related to channel access procedure, scheduling mechanism, channel state feedback techniques etc., are still under contemplation. Even so, because of its superiority in various network conditions, MU-MIMO can be expected to become one of the basic essentials of the future wireless networks and their standards. For example, IEEE 802.11ac Task Group (TG) is now working to extend IEEE 802.11n like capabilities in the 5 GHz spectrum with wider channels, better modulation schemes, and MU-MIMO inclusion.

As mentioned earlier, modification in CSMA/CA is a simplest approach towards MU-MIMO aware MAC protocol design. In fact, modification in CSMA/CA is required to accomplish CSI of all the intended receivers at the transmitter such that the transmitter can know about interference situation of its receivers and apply interference limited precoding, also known as interference limited data preprocessing, prior to data transmission in such a way that the co-users interference can be mitigated at receiver (detail in the following section) [48]-[50].

Basically, CSI can be accomplished from three different ways: perfect feedback with full channel information, partial feedback with limited channel information, and fully blind feedback with no channel information. Obviously, based on these mechanisms, several modification schemes in CSMA/CA can be provisioned to support MU-MIMO. Hence it is important to understand their performance benefits and trade-offs. Indeed, as CSMA/CA is often criticized for its bounded performance (occurrence of throughput limit and delay limit due to the effects of indispensable overhead associated with its fundamental operation), understanding their achievable performance and their performance limits are also important to reflect their deliverables. Therefore, the performance characterization (study, analysis, and comparison) of the modification approaches after applying above mentioned feedback mechanisms is the matter of interest in this chapter.

4.3 MU-MIMO System: Overview

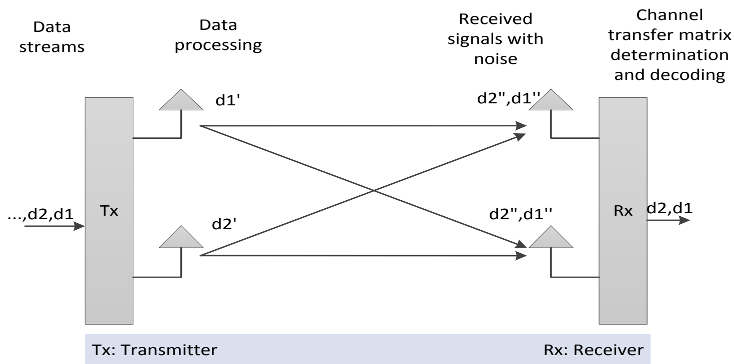


Figure 4.1: SU-MIMO transmission

From Chapter 2, it is well known that in a SU-MIMO system with M transmit and N receive antennas, capacity grows linearly with $min(M, N)$. In SU-MIMO channels, the benefit of MIMO processing is gained from the coordination of processing among all the transmitter or receiver antenna elements (channel transfer matrix determination), as shown in Fig. 4.1. However, in the MU-MIMO channel, it is usually assumed that there is no coordination among the users. A lack of coordination between users arises the inter-user interference problem.

The MU-MIMO transmission where the transmitter is simultane-

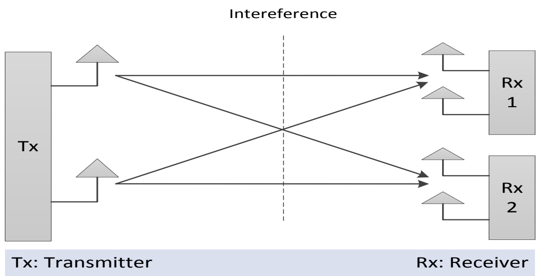


Figure 4.2: MU-MIMO transmission

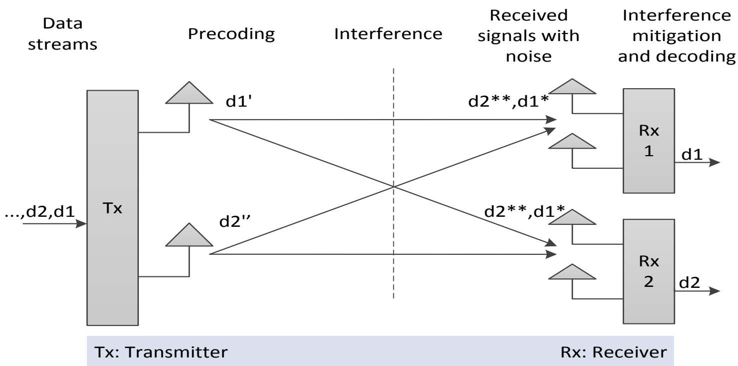


Figure 4.3: MU-MIMO interference mitigation

ously transmitting to two users over the same channel is illustrated in Fig. 4.2. In the situation depicted, it can be observed that there occurs some inter-user interference. Even so, similar capacity scaling as SU-MIMO can be achieved if appropriate signal processing (precoding) is applied in prior to the data transmission (as shown in Fig. 4.3).

If CSI is available at the transmitter, it is aware of what interference is being created for one user by the signal it is transmitting to another user and vice versa. This inter-user interference can be mitigated by the techniques such as intelligent beamforming or the use of dirty paper codes.

Intelligent beamforming is a linear precoding technique. Let us consider MU-MIMO system where the transmitter has N transmit and receive antenna elements. With N transmit antennas the transmitter can transmit a total of N spatial streams. These N streams can be distributed across a maximum of N users. When the transmitter transmits different streams to multiple users, streams intended for one user will cause interference to the other users. This is represented by the following equation,

$$y_i = \sqrt{\frac{\rho}{N}} h_i w_1 x_1 + ... + \sqrt{\frac{\rho}{N}} h_i w_i x_i + ... + \sqrt{\frac{\rho}{N}} h_i w_N x_N + n_i$$

$$= \sqrt{\frac{\rho}{N}} [w_1, ...w_N] \begin{bmatrix} x_1 \\ x_2 \\ . \\ . \\ . \\ x_N \end{bmatrix} + n_i \tag{4.1}$$

Where, y_i is the received signal at user i, x_i is the transmitted stream to the user i, h_i is the channel coefficient between the transmitter and the user i, w_i is the weight applied at the transmitter, ρ is the received power, n_i and is the adaptive white Gaussian noise.

The signal $h_i w_i x_i$ received causes interference when decoding its streams x_i for $i \neq j$. However, the transmitter can mitigate this interference with the intelligent beamforming techniques. For example, if we select weights in such a way that $h_i w_j = 0$, interference from other users will be canceled out. The simple approach is to precode the data with pseudo-inverse of the channel matrix. To avoid the noise enhancement that accompanies such zero forcing techniques, the Minimum Mean Square Error (MMSE) precoding can be used instead. To describe the approach, let us consider the following system model.

$$\begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ . \\ y_N \end{bmatrix} = \sqrt{\frac{\rho}{N}} \begin{bmatrix} h_1 \\ h_2 \\ . \\ . \\ . \\ h_N \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ . \\ . \\ . \\ w_N \end{bmatrix}^T \begin{bmatrix} x_1 \\ x_2 \\ . \\ . \\ . \\ x_N \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ . \\ . \\ . \\ n_N \end{bmatrix} \tag{4.2}$$

In general, the above equation can be represented as,

$$y = \sqrt{\frac{\rho}{N}} HWx + n \tag{4.3}$$

The MMSE precoding weights are then given as,

$$w = \sqrt{\frac{\rho}{N}} H^+ \left(\frac{\rho}{N} HH^+ + \phi_z \right)^{-1} \tag{4.4}$$

Where, ϕ_z is the noise covariance matrix and H^+ is the Hermitian of H. If we have CSI of every links, we can easily apply precoding and reduce down the interference at transmitter side. Again, if CSI is available at receiver, the interference can be further reduced at the receiver side using the equalizer. In this case, transmitter selects weight on such a way that it does not interfere the transmitted signals while receiver selects weight on such a way that it receives only the signal of interest and is not interfered by other signals.

Dirty paper coding technique is the nonlinear precoding technique which is based on the concept of "writing on dirty paper" introduced by Costa [51]. In this technique, the traditional additive Gaussian noise channel is modified to include an additive interference term that is known at the transmitter:

$$\textit{received signal}=\textit{transmitted signal}+\textit{interference}+\textit{noise}.$$

The concept of dirty paper coding relies on the point that writing on dirty paper is information theoretically equivalent to writing on clean paper when one knows in advance where the dirt is. In MU-MIMO transmission, because the transmitter has CSI of all its receivers, it knows what interference one user's signal will produce at another user, and hence can design a signal for another user on such a way that it avoids the known interference.

The most well-known dirty paper technique for the MU-MIMO uses a QR decomposition of the channel. It can be presented as the product of a lower triangular matrix L with a unitary matrix $H = LQ$. The signal to be transmitted is precoded with the Hermitian transpose of Q, resulting in the effective channel L [52]. The first user of this system sees no interference from other users so that its signal may be chosen without regard for the other users. The second user sees interference only from the first user so that the interference is known and thus can be overcome using coding.

4.4 MU-MIMO aware MAC Modification Requirements

Basically, a precoder has two effects: decoupling the input signal into orthogonal spatial modes and allocating power over these beams based on the CSI. If the precoded, orthogonal spatial-beams match the channel eigen-directions (the eigenvectors of $H.H$), there will be no interference among signals sent on different modes, thus creating parallel channels and allowing transmission of independent signal streams. Therefore, CSI is not only useful in achieving high SNR at the desired receiver, but also in reducing the interference produced at other points in the network. The most common method for obtaining CSI at the transmitter is through the use of training or pilot data or via feedback of the receivers channel estimate.

In this chapter, we investigate three basic types of modification approaches that best represent the possible modifications in CSMA/CA

Frame Control	Duration	K*Receiver Address	Transmitter Address	Frame Check
2 bytes	2 bytes	K x 6 bytes	6 bytes	4 bytes

M-RTS Frame

Figure 4.4: M-RTS control packet format

to upgrade it into MU-MIMO aware CSMA/CA, named as: (a) CSI feedback from serially transmitted CTS packets, (b) CSI prediction from serially transmitted CTS packets, and (c) CSI prediction from simultaneously transmitted CTS packets.

4.5 MU-MIMO aware CSMA/CA

MIMO aware CSMA/CA is an extended version of CSMA/CA RTS/CTS mechanism. Although the main purpose of RTS/CTS mechanism is to reserve a channel for a duration of packet transmission with exchange of channel reservation parameters, it can also serve to exchange information related to MIMO functionalities after applying frame extension. The extended version of the control packets append a new field or a header dedicated for managing the MIMO functionalities while keeping the rest of the fields unchanged.

In MU-MIMO, a transmitting node transmits X independent parallel data streams from X transmit antenna elements to K nodes $(X \times K)$, $K \leq X$ by applying interference limited precoding. Hence, in MU-MIMO aware CSMA/CA, when the transmitting node has packets

Frame Control	Duration	Receiver Address	CSI	Frame Check
2 bytes	2 bytes	6 bytes	X x K bytes	4 bytes

M-CTS Frame I

Figure 4.5: M-CTS control packet format for CSIF-STCP

to send it first acquires the channel using the CSMA/CA standard rule. After acquiring the channel, it transmits an extended RTS (M-RTS) packet, as shown in Fig. 4.4, explicitly including the information about K receivers addresses[2], serially. All other fields contain the regular information as they do in legacy RTS packet. After a SIFS time interval, along with other regular information, receiving nodes which are ready to receive reply with individual extended CTS (M-CTS) packet containing information that could be processed to achieve CSI. The M-CTS and extended Acknowledgement (M-ACK) packet exchange mechanisms and the frame formats are different for different modification approaches. For our investigated approaches, it is discussed in detail below.

4.5.1 CSI Feedback From Serially Transmitted CTS Packets (CSIF-STCP)

In this modification approach, RTS/CTS handshake can be modified to allow their receiver to feedback CSI corresponding to received signal

[2]Size of the RTS "*Receiver Address*" field is increased by $K-1$ times in M-RTS

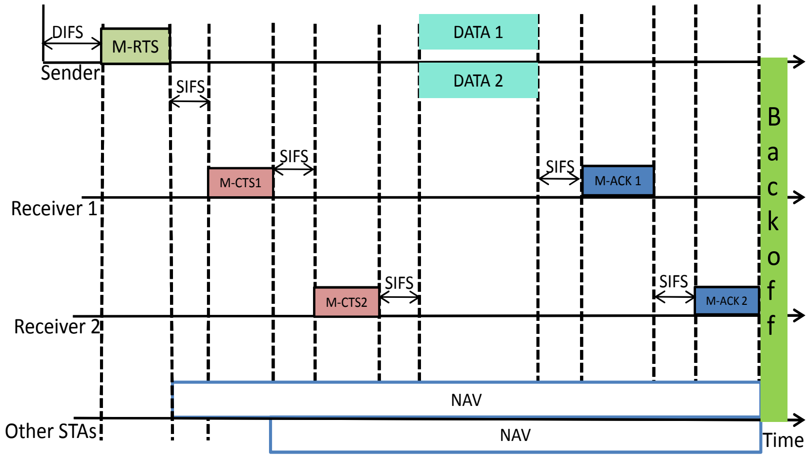


Figure 4.6: Channel access mechanism in CSIF-STCP and CSIP-STCP

Frame Control	Duration	Receiver Address	Frame Check
2 bytes	2 bytes	6 bytes	4 bytes

M-CTS Frame II

Figure 4.7: M-CTS control packet format for CSIP-STCP and CSIP-SmTCP

using M-CTS packet, as shown in Fig. 4.5. All receivers estimate their channel from received M-RTS packet and, along with other regular information, feedback that value to transmitter by sending individual M-CTS packet after each SIFS time interval, as shown in Fig. 4.6 for 2×2 MU-MIMO, according to their serial order assigned in M-RTS packet. Based on the information received from M-CTS packets, the transmitting node selects the best antenna element corresponding to each receiver node and then applies appropriate precoding. Similarly after each SIFS time interval, receiver nodes successfully receiving the data stream acknowledge the reception via M-ACK, serially. Therefore this method can be considered as the perfect CSI feedback method. This is the simplest and the most effective method despite the introduced overhead resulting from transmission of multiple extended M-CTS and M-ACK packets serially. This mechanism, however, reduces the cost and complexity in signal processing and also minimizes the risk of control packets corruption.

4.5.2 CSI Prediction From Serially Transmitted CTS Packets (CSIP-STCP)

In this modification approach, different from the CSIF-STCP mechanism, the M-CTS packet does not explicitly contain the CSI, instead receivers can send M-CTS packet in the same order as in CSIF-STCP, i.e. serially after each SIFS time interval, but with pre-defined pilot symbols included in the PHY header. From the enclosed pilot symbol, with appropriate signal processing, the transmitter node can predict the CSI corresponding to the respective receiver node based on reciprocity principle, i.e. in the assumption of same channel characteristics in uplink and downlink in contiguous transmission with TDMA. This method can be considered as a semi blind channel state estimation method as limited information is provided by pre-defined pilot symbols. After predicting CSIs, the transmitter can apply appropriate precoding and then send the data streams. M-ACK packets are also transmitted in the same way as in CSIF-STCP, i.e. serially. Hence, as a whole, this mechanism reduces the overhead that results from feedback bits in spite of moderate rise in the prediction burden. Even so, since M-CTS packets are transmitted serially, there is less chance of packets being corrupted and in most of the cases prediction was found to work quite well.

4.5.3 CSI Prediction From Simultaneously Transmitted CTS Packets (CSIP-SmTCP)

In this modification approach, different from CSIF-STCP and CSIP-STCP, M-CTS packets are not transmitted serially. Instead they are transmitted simultaneously after a SIFS time interval by all the receiver nodes including the predefined pilot symbol in the PHY header as in CSIP-STCP. This method can be considered as a full blind channel state estimation method despite the inclusion of the pre-defined pilot symbol. As the receiver nodes transmit in same time and frequency domain, decoding the information completely comes as blind. Nevertheless, employing available antenna elements and the appropriate signal processing (Multiuser Detection (MUD) process), the transmitter node can predict the CSI of all receiver nodes and can apply appropriate precoding. The M-ACK packets are also transmitted in the same way. The M-CTS frame format and the access mechanism for this approach have been shown in Fig. 4.7and Fig. 4.8, respectively.

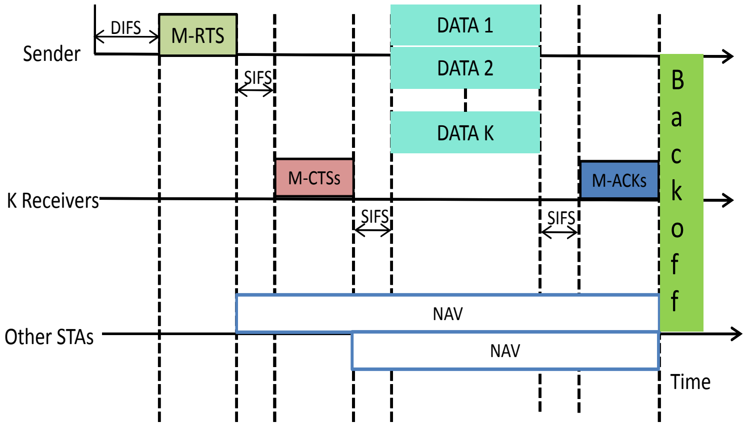


Figure 4.8: Channel access mechanism for CSIP-SmTCP

This mechanism reduces the overhead that could result from transmission of feedback bits as in CSIF-STCP and overhead that could result from serially transmitted M-CTS packets as in CSIF-STCP and CSIP-STCP. However, this mechanism adds higher cost and complexity in signal processing and may also raise the risk of control packets corruption.

4.6 Numerical Analysis

4.6.1 Mathematical Analysis for Achievable Performance

Achievable maximum performance of a system, as stated before, is the performance that the system can deliver in the best case scenario. In order to emulate the best case scenario here, we abide by the following assumptions: (a) there is only one active transmitting node which always has packets to send, and (b) the channel is error free. Considering the aforementioned assumptions, we analyze the achievable maximum performance of our investigated approaches in terms of throughput and delay. Hereafter we represent $CSIF - STCP$, $CSIP - STCP$, and $CSIP - SmTCP$ as M_1, M_2, and M_3, respectively.

4.6.1.1 Maximum Achievable Throughput

As throughput is the rate of successful transmission of the data packets in the channel, the maximum achievable throughput, S^{max}, for the MU-MIMO can be expressed as,

$$S^{max} = \frac{\sum_{j=1}^{K} E[P]}{T_s}, \tag{4.5}$$

where $E[P]$ is the payload size in bits and T_s is the time for a successfully transmitting those bits. T_s for all three modifications approaches, T_{s,M_1}, T_{s,M_2}, and T_{s,M_3}, are different from each other because of the differences in M-RTS, M-CTS, and M-ACK packet formats and/or exchange mechanisms. However, it is important to note that mathematical expressions for M_1 and M_2 remain same as the changes only occur in frame formats but not in the exchange mechanisms.

$$\begin{aligned} T_{s,M_1/M_2} &= \overline{W} \times \sigma + T_{DIFS} + T_{M-RTS} \\ &+ 2KT_{SIFS} + KT_{M-CTS} + T_{HDR} \\ &+ T_{E[P]} + KT_{M-ACK}, \end{aligned} \tag{4.6}$$

$$\begin{aligned} T_{s,M_3} &= \overline{W} \times \sigma + T_{DIFS} + T_{M-RTS} + 3T_{SIFS} \\ &+ T_{M-CTS} + T_{HDR} + T_{E[P]} + T_{M-ACK}. \end{aligned} \tag{4.7}$$

Where $\overline{W}$ is the average backoff value, σ is the slot time, and $T_{(.)}$ indicates the total time required for sending respective packet. The header, HDR, consists of both the physical and MAC headers. By replacing T_s in (1) with T_{s,M_1}, T_{s,M_2}, and T_{s,M_3}, the maximum achievable throughput for all three modification approaches, $S_{M_1}^{max}$, $S_{M_2}^{max}$ and $S_{M_3}^{max}$, can be obtained.

4.6.1.2 Minimum Achievable Delay

As access delay is the time interval from the moment a node is ready to access the medium to the moment the transmission is successfully finished, the achievable minimum delay for the investigated approaches, $D_{M_1}^{min}$, $D_{M_2}^{min}$, and $D_{M_3}^{min}$ can be expressed as (4.4) and (4.5). Note that mathematical expressions for M_1 and M_2 remain same here as well.

$$
\begin{aligned}
D_{M_1/M_2}^{min} &= \overline{W} \times \sigma + T_{DIFS} + T_{M-RTS} \\
&+ KT_{SIFS} + KT_{M-CTS} + T_{HDR} + T_{E[P]},
\end{aligned} \tag{4.8}
$$

$$
\begin{aligned}
D_{M_3}^{min} &= \overline{W} \times \sigma + T_{DIFS} + T_{M-RTS} \\
&+ 2T_{SIFS} + T_{M-CTS} + T_{HDR} + T_{E[P]}.
\end{aligned} \tag{4.9}
$$

4.6.2 Mathematical Analysis for Average Performance

The carried numerical analysis follows a modular approach. Firstly, we analyze the behavior of a single tagged node by formulating a single dimensional Markov model as in [53]. With aid of the formulated model, the probability τ that the node starts to transmit in a randomly chosen slot time is calculated. Secondly, we express the average throughput and average packet delay as a function of τ. The assumptions made for the analysis are as follows: (a) the number of nodes in the network are finite (say n), (b) the nodes always have packets to transmit, and (c) the channel is idle. The probability that a node transmits in a randomly chosen slot while employing default contention resolution algorithm, Binary Exponential Backoff (BEB), can be derived as follows.

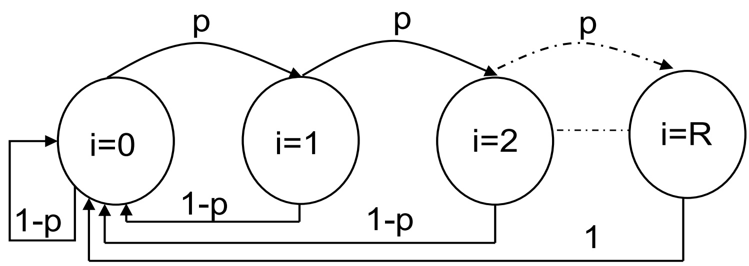


Figure 4.9: Markov chain model

In MU-MIMO transmission, collision occurs if two or more than two transmitter start their transmission at same time slot. In case of the collision, the collided nodes randomly select backoff values from the range of Contention Window (CW) according to BEB algorithm and wait till the values defer to 0. The random value is the number of transmitting opportunities that the node must give up before starting next transmission. In BEB, as the number of retransmission attempts increases, the waiting time for retransmission increases exponentially in the order of 2.

Let i be the number of contention states, $0 \leq i \leq R$. Here, R is the maximum allowed retransmission state, after which node drops the packet. Transmitting node can transit the states up to the state R by increasing value of i by 1 in every successive collision. While, in case of successful transmission, the node resets its state to 0. If we assume SS_i is the i^{th} state of the node, after sending M-RTS packet at state i, the node can enter either into next state $i + 1$ (i.e. $SSi + 1$) or 0 (i.e. SSo) depending upon the success or collision of the transmitted packet, respectively. If we assume p is the probability of collision, from the Markov chain analysis, as shown in Fig. 4.9, SS_i is the chain with the transition probabilities $p_{i,z}$, $i, z = 0, 1, ..., R$. The transition probabilities can be expressed as follows.

$$p_{i,0} = P_r\{SS_{i+1} = 0 \mid SS_i = i\} = 1 - p. \tag{4.10}$$

$$p_{i,i+1} = P_r\{SS_{i+1} = i + 1 \mid SS_i = i\} = p. \tag{4.11}$$

$$P_{R,0} = P_r\{SS_0 = 0 \mid SS_R = R\} = 1. \tag{4.12}$$

If we take τ as the relative frequency to enter the state i, we can define τ as,

$$\tau = \frac{1}{1 + \frac{1-p}{1-p^{R+1}} \sum_{i=0}^{R} p^i E[b_i]}. \tag{4.13}$$

Here $E[b_i]$ is the average backoff time in contention stage i. $E[b_i]$ for stage i is $\frac{W_i}{2}$, where W_i is the maximum contention window size in contention stage i.

In the stationary state, a node transmits a packet with probability τ. So the collision probability, p, i.e. probability of transmission of other nodes at same arbitrary time slot, can be expressed as,

$$p = 1 - (1 - \tau)^{n-1}. \tag{4.14}$$

Equations (6) and (7) represent nonlinear systems with two unknowns, τ and p, which can be solved using numerical methods to get a unique solution. When τ and p are obtained, performance metrics like throughput and delay can be derived considering other system parameters.

4.6.2.1 Average Throughput

Throughput is one of the most important indicators to evaluate network performance. Throughput can be defined as the rate of successful transmission of the data packets over the channel. Thus, throughput for MU-MIMO, S, can be related as,

$$S = \frac{P_s P_{tr} \sum_{j=1}^{K} E[P]}{(1 - P_{tr})T_i + P_s P_{tr} T_s + (1 - P_s) P_{tr} T_s}, \tag{4.15}$$

where P_{tr} is the probability that there is at least one transmitting node active in the considered slot time and P_s is the probability that the transmission is successful. P_{tr} and P_s can be obtained easily when τ and p are known. T_s and T_c are the average time the channel is sensed to be busy because of successful transmission or collision, respectively, while T_i is the duration of an empty slot time. T_s and T_c for our investigated approaches can be derived as follows.

$$\begin{aligned} T_{s,M_1/M_2} &= T_{DIFS} + T_{M-RTS} + 2KT_{SIFS} \\ &+ KT_{M-CTS} + T_{HDR} + T_{E[P]} \\ &+ KT_{M-ACK}, \end{aligned} \tag{4.16}$$

$$T_{s,M_3} = T_{DIFS} + T_{M-RTS} + 3T_{SIFS} \tag{4.17}$$
$$+ \; T_{M-CTS} + T_{HDR} + T_{E[P]} + T_{M-ACK},$$

$$T_{c,M_1/M_2/M_3} = T_{DIFS} + T_{M-RTS}. \tag{4.18}$$

4.6.2.2 Average Delay

Packet delay is defined as the time interval from the time a packet is at the head of its MAC queue ready to be transmitted until the ACK for that packet is received. Average packet delay, D, can be derived by following the model in [53], and for the MU-MIMO it can be expressed as

$$D = \frac{n}{\overline{S}/E[P]} - E[slot](1 - B_0)\frac{p^{R+1}}{1 - p^{R+1}}\sum_{i=0}^{R}(1 + E[b_i]), \tag{4.19}$$

where $\overline{S}$ is the throughput with single antenna element while $E[slot]$=$(1-P_{tr})T_i + P_sP_{tr}\overline{T_s} + (1 - P_s)P_{tr}\overline{T_s}$. Here, $\overline{T_s}$ is the average of the successful transmission times with respective antenna elements and $B_0 = \frac{1}{W_0}$.

4.7 Performance Evaluation and Discussion

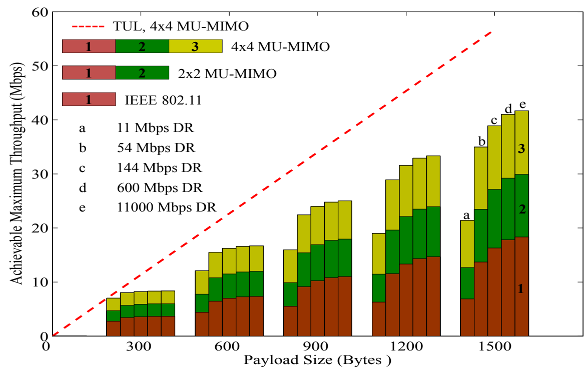
We evaluate the performance numerically based on the above presented mathematical expressions taking into consideration all the parameters presented in Table 4.1. The selected parameters have been adopted in

Table 4.1: System parameters considered for performance analysis of MU-MIMO aware MACs

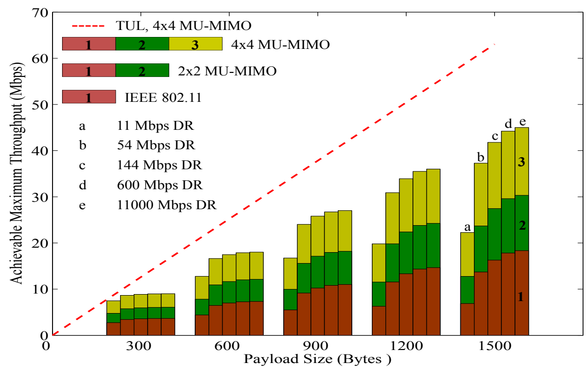
Parameters	**Value**
MAC header	272 bits
PHY header	40 μs
ACK packet	112 bits
DIFS	50μs
SIFS	10μs
Slot time	20μs
Basic data rate	6 Mbps
Available antenna	1, 2, 4
Minimum contention window (W)	16
Maximum retry limit (R)	6

such a way that they could insure the interoperability between MIMO adapted and MIMO less WLANs. The MAC header and PHY header parameters are adopted from IEEE 802.11n mixed mode transmission. Slight modification in headers has been applied to accomplish maximum 4 numbers of MU-MIMO receivers. Rests of the parameters are adopted from IEEE 802.11g. Extended RTS and CTS frames are used as described earlier.

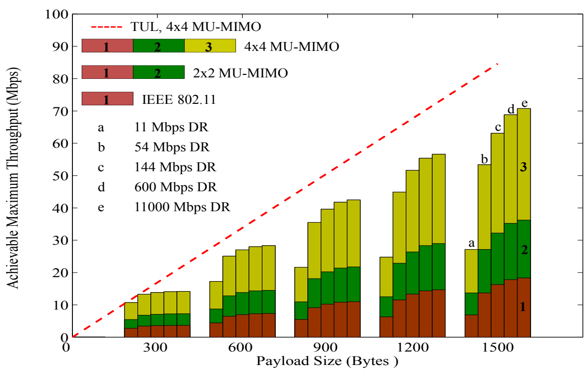
Achievable maximum throughput and achievable minimum delay with respect to $E[P]$ for different $X \times K$ configuration and for different channel Data Rate (DR) are presented in Fig. 4.10 (a), (b), (c) and Fig. 4.11 (a), (b), (c), respectively, for M_1, M_2, and M_3. It is important to note that the achievable throughput increases with the number of antenna elements and DR, and the achievable minimum delay decreases with an increase in DR but increases with antenna elements. However, it is evident that from a PHY point of view achievable throughput



(a) M_1 (CSIF-STCP)

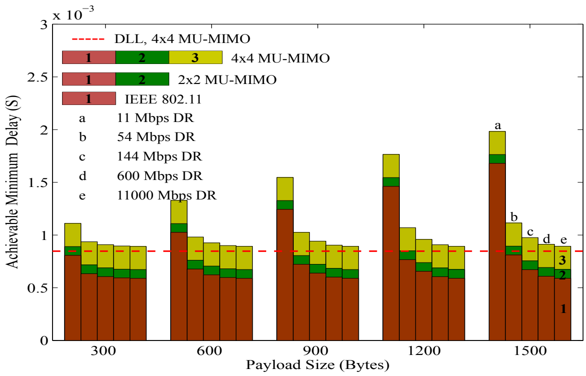


(b) M_2 (CSIP-STCP)

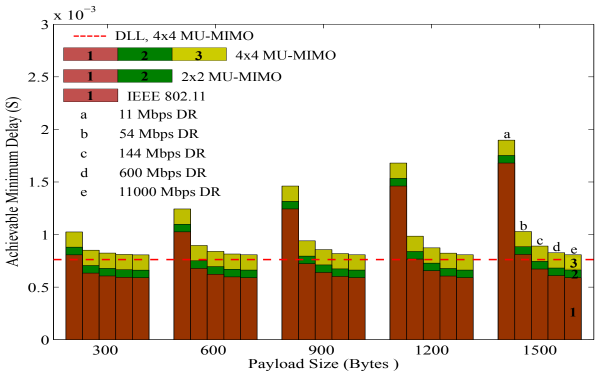


(c) M_3 (CSIP-SmTCP)

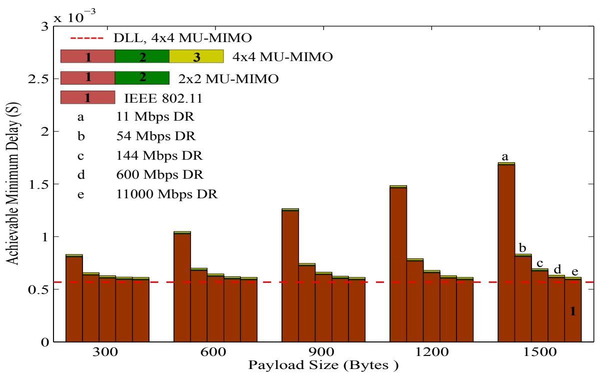
Figure 4.10: Achievable maximum throughput of MU-MIMO aware MAC protocols



(a) M_1 (CSIF-STCP)



(b) M_2 (CSIP-STCP)



(c) M_3 (CSIP-SmTCP)

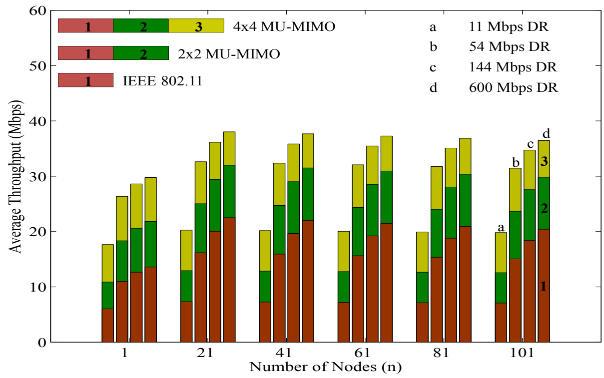
Figure 4.11: Achievable minimum delay of MU-MIMO aware MAC protocols

should increase with an increase in antenna elements and DR, as the channel capacity increases with them. Similarly, the achievable minimum delay should decrease with an increase in DR and should show no indication of changes on antenna elements variation, as simultaneous transmission with MIMO means concurrent transmissions on same time and frequency domain. In these results $S^{max}_{M_1} < S^{max}_{M_2} < S^{max}_{M_3}$ and $D^{min}_{M_1} > D^{min}_{M_2} > D^{min}_{M_3}$. These results show the effects of overheads associated with each of the modification approaches. As mentioned earlier, in order to solve the important MAC layer issues like MIMO functionalities information exchange and error free control packets reception, a MAC protocol needs to exchange different extended control packets with cost of additional overhead. Similarly, when the number of antenna elements increases more control packets exchange is required to associate each of the elements again in cost of additional overhead. The results reveal that in the investigated approaches M_1 has higher overhead compared to M_2 and M_3. Similarly, M_2 has higher overhead compared to M_3. However, the resulting effects observed here are not only from the overhead associated with extended control packets but also from basic CSMA/CA operation and its requirement of control packets exchange in lower transmission rate.

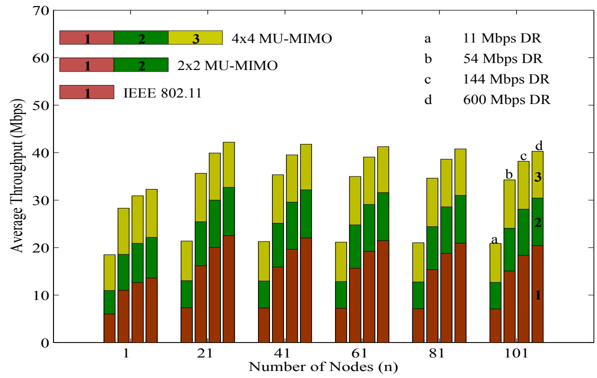
Apart from this, the results also show that the throughput does not increase linearly in M_1 and M_2 while in M_3 it increases more or less linearly with antenna elements but not with DR. Note that in all these cases there is no linear throughput-delay gain with respect to

DR. Even for the infinite DR the throughput bounds to Throughput Upper Limit (TUL) and delay bounds to Delay Lower Limit (DLL). It can also be observed that for M_3, in spite of our assumption of no additional overhead during the modification, the performance goes towards bounding because of overhead related to basic CSMA/CA operation and its requirement of control packets transmission in lower transmission rate.

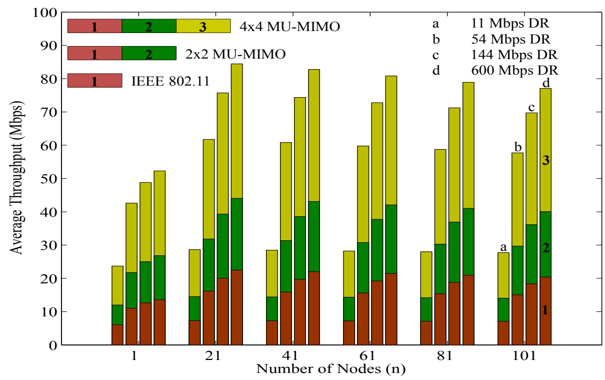
Average throughput with respect to n for different $X \times K$ configuration and with different DR for M_1, M_2, and M_3 are presented in Fig. 4.12 (a), (b), and (c), respectively. It can be seen that throughput increases with antenna elements and DR. The results also show $S_{M_1} < S_{M_2} < S_{M_3}$. These results again depict the overhead's effect and effects related to basic CSMA/CA operation and its requirements as mentioned above. In addition, it can be observed that throughput increases in the beginning when n starts to increase but after reaching a certain threshold the throughput starts to decrease. This is because when there are only fewer number of nodes there will be higher probability of the slots remaining idle due to waiting time associated with backoff algorithm. But, initially when the number of nodes starts to rise, the throughput increases as the probability of slots remaining idle gets reduced. However, when n increases further the probability of collision also increases which ultimately reduces the throughput. Besides these observations, the throughput does not increase linearly in M_1 and M_2 while in M_3 it increases more or less linearly with antenna



(a) M_1 (CSIF-STCP)

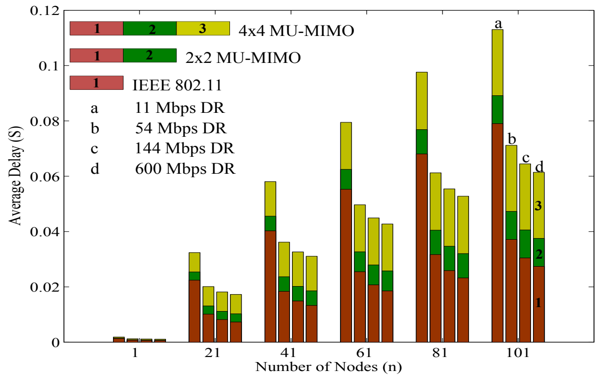


(b) M_2 (CSIP-STCP)

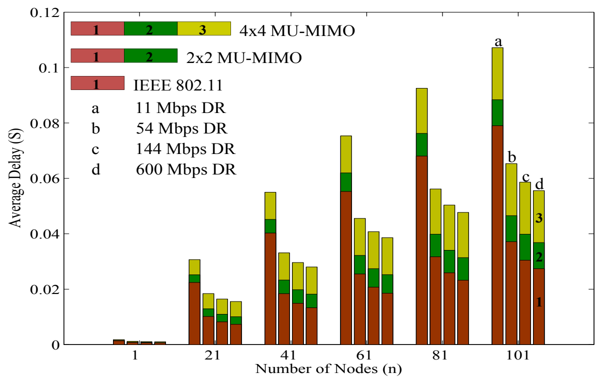


(c) M_3 (CSIP-SmTCP)

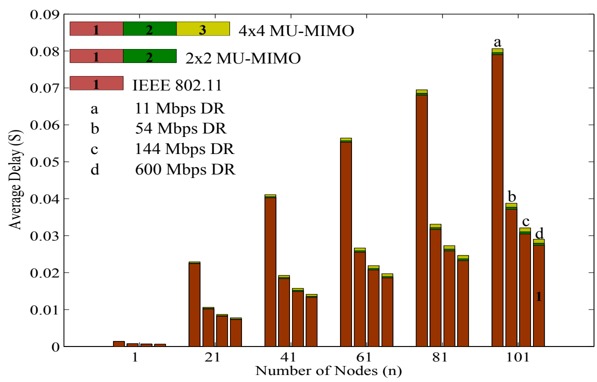
Figure 4.12: Average throughput of MU-MIMO aware MAC protocols



(a) M_1 (CSIF-STCP)



(b) M_2 (CSIP-STCP)



(c) M_3 (CSIP-SmTCP)

Figure 4.13: Average delay of MU-MIMO aware MAC protocols

elements like in the previous results. Figure 4.13 (a), (b), and (c) show the average delay results for M_1, M_2, and M_3, respectively. It can be seen that the delay increases with antenna elements but in opposite decreases with DR. However in these results as well, $D_{M_1} < D_{M_2} < D_{M_3}$ due to overhead's effect and basic CSMA/CA operation's effect as mentioned above. Moreover, it can also be remarked that the delay increases with n in all cases as the addition in number of nodes causes the higher probability of collision and leads to high waiting time. Similar to the previous results there is no linear throughput-delay gain in these results as well.

As far as we have discussed, the major factor that bounds throughput and delay is the overhead associated per successful data transmission when adapting conventional CSMA/CA. Clearly from our results the overhead's effect can be reduced at the cost of complexity. Hence, performance and complexity can be flexibly traded off against each other. Apart from this, in MIMO aware CSMA/CA, along with the modifications in control packet formats and/or channel access mechanism, other schemes to reduce overheads like frame aggregation, block acknowledgement, etc., should also be investigated parallelly to better utilize MIMO capacity.

4.8 Concluding Remarks

We characterized the performance of CSMA/CA adapted MU-MIMO aware MAC in widely deployed WLANs. Along with the discussion on modification approaches that best represent the possible ways to upgrade conventional CSMA/CA into MU-MIMO aware CSMA/CA, we provided their detailed performance analysis, based on the analytical modeling and derived expressions, in terms of throughput and delay. Thus, on one hand, after presenting the importance of MU-MIMO aware MAC protocol, we presented the discussion on modification approaches and the analytical model to understand their performance, while on the other hand, we also showed the limitations of such protocols due to the effects of indispensable overhead associated.

5 Enhanced MIMO aware MAC Protocol for MU-MIMO Reception

In this chapter, we present a simple contention based multi-request transmission scheme based on CSMA/CA to facilitate the MU-MIMO reception in WLANs uplink.

5.1 Motivation

In an infrastructure based WLANs with MIMO systems, AP can initiate the multi-user MIMO transmission (spatially multiplexed data streams to multiple users in downlink) by broadcasting the request to send packet. However, on oppose to the downlink, multi-user MIMO reception (spatially multiplexed data streams from multiple users in uplink) is not as easy as the distributed nodes have to initiate their own transmission without negotiation with each other. In this chapter, by employing contention based multi-request transmission scheme as a supplementary scheme to CSMA/CA and with the implementation of modified control packets, we present a MAC protocol that is capable of supporting MU-MIMO reception in WLANs. Provided with optimal contention parameter set up, the proposed MAC protocol achieves more benefits in terms of throughput.

5.2 Introduction

In downlink of infrastructure based WLANs with MIMO, AP can initiate MU-MIMO transmission by broadcasting the request to send packet to multiple intended receivers. However, it is not as easy in MU-MIMO reception case in uplink, as the distributed nodes have to initiate their own transmission without negotiation with each other. If the number of transmitting node is less than or equal to the number of antenna elements in AP, AP can receive all the transmitted streams using all its antenna elements and decode the signal by employing Multiuser Detection Technique (MUD). However, if the number of transmitting node is greater than the number of receiving antenna elements in AP, all the transmitted signals suffers with interference and AP could decode the signals. On the other hand, if only a particular node is allowed to transmit at a time, like conventional CSMA/CA, the available MIMO capacity in AP may not be utilized fully during the transmission of nodes with less number of antenna elements than AP. Therefore, to realize the advantages of MU-MIMO reception over existing WLANs, it again requires significant changes in the CSMA/CA MAC protocol.

In this chapter, by employing contention based multi-request transmission concept with modified control packets exchange scheme as a supplementary scheme to the conventional CSMA/CA, we propose a MAC protocol that supports MU-MIMO reception in WLANs. Under this scenario, the system performance may depend on the set of transmitting users. Provided with optimal contention parameters set up, the proposed protocol achieves more benefits in terms of throughput.

5.3 MIMO aware CSMA/CA for MU-MIMO Reception

In MU-MIMO reception, X transmitter nodes transmit J, $X \leq J$, independent parallel data streams from j antenna elements to a node with K antenna elements, $K \geq J$. Hence, in the proposed protocol, when any one transmitting node acquires the channel using the CSMA/CA standard rule, it transmits RTS packet. We call this node a primary node. After SIFS time interval, AP ready to receive replies with CTS packet. However, in this phase, if $J = K$, then AP sends the regular CTS packet intended only to the primary node and the primary node sends K parallel data streams after SIFS. On the other hand, if $J < K$, then AP sends extended CTS packet, eCTS, appending the information about the number of additional spatial streams D, $D = K - J$, that it can support in the same transmission round. Along with the information about D, AP also sends the contention parameter (contention window size) m. If there is N number of nodes in the network, then n number of nodes out of remaining $N - 1$ number of nodes randomly selects one slot out of m slots and transmits the extended RTS (eRTS) packet. We call this the second round of

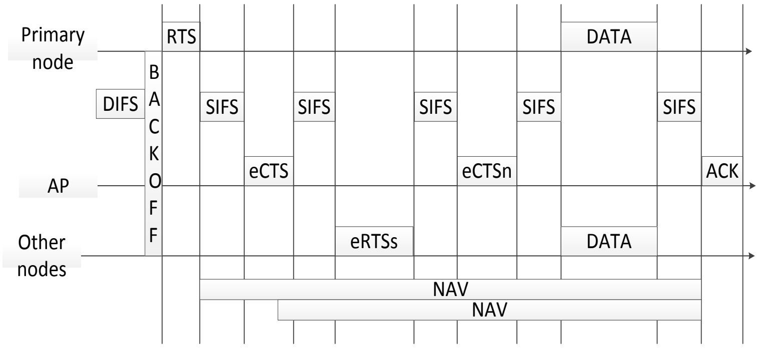


Figure 5.1: MU-MIMO aware MAC for MU-MIMO reception

contention. Among n contending nodes AP selects S , $1 \leq S \leq D$, number of nodes and again sends new eCTS (eCTSn) including the addresses of the selected node(s). Then after SIFS, the selected nodes along with the primary node send the parallel data streams. Finally, after SIFS, AP broadcasts the extended ACK (eACK). The channel access procedure for this scheme has been shown in Fig. 5.1.

5.4 Numerical Analysis

The carried numerical analysis follows a modular approach. Firstly, we analyze the behavior of a primary node by formulating one dimensional Markov model as in chapter 4 for first round of contention. Secondly, we analyze the contention based multi-request transmission approach, i.e. second round of contention. According to the analyzed expressions we derive the relation for the average throughput performance. The assumptions made for the analysis are as follows: (a) number of nodes in the network are finite (say N), (b) nodes always have packets to send, (c) channel is idle, and (d) n out of N number of nodes compete for second round of contention. Probability that a primary node transmits in an arbitrary time slot while employing default contention resolution algorithm can be derived as in (4.6). Similarly, the probability of collision cab be expressed as in (4.7)

Once we find the probability of transmission and probability of collision, we can find the probability of successful transmission of a primary node, P_s.

$$P_s = \frac{N\tau(n-\tau)^{N-1}}{P_{tr}}. \tag{5.1}$$

Here, P_{tr} is the probability that at least one node transmits out of N nodes and can be expressed as,

$$P_{tr} = 1 - (1-\tau)^N. \tag{5.2}$$

Now, when a primary node acquires a channel, then AP analyses number of spatial streams that can be supported and the number of nodes that are going to participate in the second round of contention and then sends reply packet accordingly as mentioned above. Then n number of nodes competes for the channel with contention parameter m. In this process, the probability of survival, P_{sr} of at least s eRTSs can be expressed by the following combinatorial problem [54].

$$P_{sr}(s,m,n) = \begin{cases} \frac{(-1)^s m! n!}{m^n s!} \sum_{j=s}^{min(m,n)} \frac{(-1)^j (m-j)^{n-j}}{(j-s)!(m-j)!(n-j)!}, & s \in [0, min(m,n)] \\ 0, \quad \text{Otherwise} \end{cases}$$

If at least one node out of n nodes successfully sends the eRTS then MU-MIMO reception is possible. Otherwise, there will be reception only from the primary node. We call this the direct reception. The probability of MU-MIMO reception can be expressed as follows,

$$P_{MU-MIMO} = P_{sr,MU-MIMO} P_s. \tag{5.3}$$

Where, $P_{sr,MU-MIMO}$ is a probability of successful transmission of at least one eRTS and can be expressed as,

$$P_{sr,MU-MIMO} = P_{tr} P_s \sum_{s=1}^{min(m,n)} P_{sr}(s,m,n). \tag{5.4}$$

Once P_{sr} is found, then the probability of channel remaining busy due to transmission of eRTSs can also be found,

$$P_b = 1 - \left(1 - \frac{1}{m}\right)^n. \tag{5.5}$$

From above eqn. average number of busy slots, $E[B]$, during transmission of eRTSs can also be found so that average busy and the idle time duration during the second round of contention can be calculated

[55].

$$E[B] = \sum_{i=0}^{m} \binom{m}{i(P_b)^i} (1 - P_b)^{m-i}. \tag{5.6}$$

Finally, the probability of direct reception, P_{dt} can be expressed as,

$$P_{dt} = 1 - P_{MU-MIMO}. \tag{5.7}$$

Once we find these probabilities, performance metric like average throughput can be easily derived considering other system parameters. As throughput is defined as the rate of successful transmission of the data packets over the channel, throughput, here represented as Z, can be related as,

$$Z = \frac{P_{MU-MIMO} \sum_{i=1}^{K} E[P] + P_{dt} E[P]}{P_i T_i + P_{ss} T_s + P_c T_c}. \tag{5.8}$$

Where, $E[P]$ is the average payload size, P_i is the probability of slots remaining idle before a primary node reserves the channel. P_{ss} is the sum of $P_{MU-MIMO}$ and P_{dt} . T_{ss} is total transmission time. P_c is the probability of collision of the primary node and T_c is the collision time of a primary node. All these expression can be expressed as,

$$P_i = 1 - P_{tr}, \tag{5.9}$$

$$P_c = 1 - P_s P_{tr}, \tag{5.10}$$

$$T_c = T_{DIFS} + T_{RTS} + T_{SIFS} + T_{CTS}, \tag{5.11}$$

$$\begin{aligned} T_{ss} &= T_{DIFS} + T_{RTS} + 4T_{SIFS} + T_{eCTS} \\ &+ E[B](T_{eRTSs} + T_{SIFS}) + (1 - P_b)T_i \\ &+ T_{eCTSn} + T_{DATA} + T_{eACK}, \end{aligned} \tag{5.12}$$

5.5 Performance Evaluation and Discussion

We evaluate the performance numerically based on the above presented equations and considering the parameters presented in Table 5.1. The parameters have been adopted in such a way that they could insure the interoperability between MIMO equipped and MIMO less nodes. The MAC header and PHY header parameters are adopted from IEEE 802.11n mixed mode transmission. Rest of the parameters is adopted from IEEE 802.11g. Extended control frames are used as described earlier. We assume the subfield bit indicates the type of the control frames.

Figure 5.2 shows the throughput performance with respect to N for fixed payload size of 1500 bytes with channel data rate 54 Mbps for different values of m. Without loss of generality, we have assumed that the AP is equipped with 2 antenna elements while the nodes are

Table 5.1: System parameters considered for performance analysis of MIMO aware MAC for MU-MIMO reception

Parameters	**Value**
DIFS	50 μ s
SIFS	10 μ s
Slot time	20 μ s
PHY header	40 μ s
MAC header	272 bits
RTS/eRTS packet	160 bits
CTS/eCTS/eCTSn packet	112/128/144 bits
ACK/eACK packet	112/144 bits
Basic data rate	6 Mbps
Minimum contention window (W)	16
Maximum retry limit (R)	6

equipped only with a single antenna. From the presented results, it can be observed that when N is low the throughput performance is high. When N goes on increasing, then the throughput goes on decreasing. It is obvious that when number of user increases, the collision probability increases in the network and the throughput decreases. Regarding the proposed protocol, however, it can be observed that when N is low the average throughput is high for lower value of m. When the value of m is increased, the throughput for low number of users decreased while the throughput for high number of users increased. On further increasing m, the throughput performance for all range of user decreased. Hence, from the presented result it can be observed that if optimal value of m is provided the proposed protocol outperforms the legacy scheme in terms of average throughput.

The optimal value of m should be chosen by the AP taking into

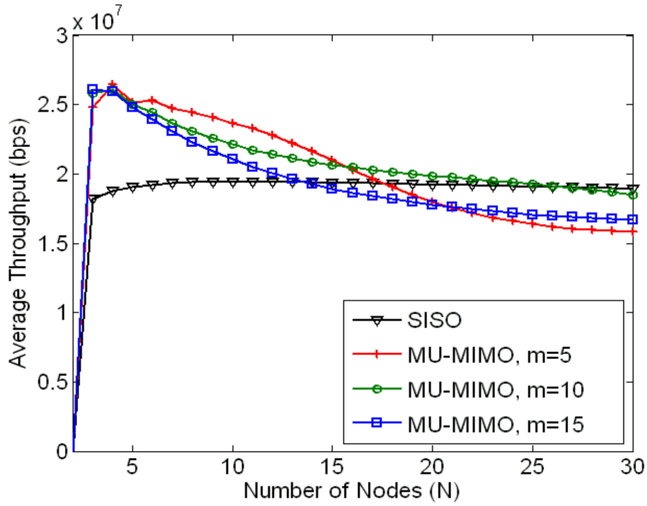


Figure 5.2: Average throughput for proposed and legacy scheme

account the number of users that will participate in the second round of contention. In our analysis, we have assumed the maximum number of possible users, i.e. $n = N-1$. However, this is more an implementation issue rather than a protocol issue. Different selection algorithms could be used in this phase. It is AP to decide the appropriate policy to choose or to estimate n. Elaborated work regarding this matter will be covered in detail in our future work.

Once the value of n is known then the corresponding value of m that gives maximum throughput performance can be simply calculated. In Fig. 5.3, upper window shows the normalized throughput (normalized by maximum throughput) for different value of m and N. The lower window of Fig. 5.3 shows the corresponding throughput value and the increment tendency of m with respect to N.

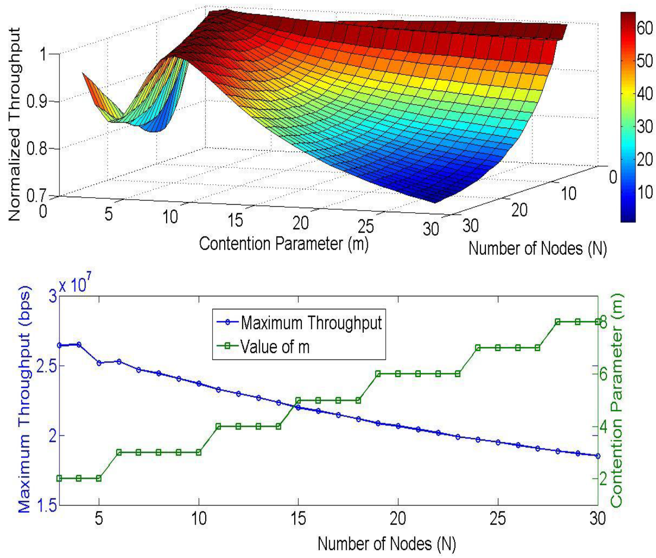


Figure 5.3: Maximum throughput and the corresponding window size

5.6 Concluding Remarks

A scheme to support MU-MIMO reception in WLANs is presented. The proposed scheme is realized only with subtle modification in the CSMA/CA protocol. Through detail analysis, it is presented that provided with optimal parameter set up, MU-MIMO reception with enhanced throughput performance can be achieved with the presented scheme.

6 Enhanced MIMO aware MAC Protocol for Efficient Transmission Mode Selection

In this chapter, we present a scheme that can work as a switching entity between MU-MIMO and multiple SU-MIMO so as to facilitate the maximum utilization of available MIMO capacity in the forthcoming VTH WLAN.

6.1 Motivation

When transmission duration varies considerably between receivers, MU-MIMO may fail to utilize the available MIMO capacity to its full potential. Transmission duration may vary due to difference in link qualities or data lengths. A MAC protocol design that can switch between MU-MIMO and multiple SU-MIMO transmissions after taking into account the achievable performance could be one of the simple yet attractive solutions to address such issue. In this chapter, by simply upgrading WLANs default MAC protocol CSMA/CA, we present a MAC protocol that is capable of performing such switching task in a forthcoming VHT WLAN. The detailed performance analysis demonstrates that more benefits could be achieved from the proposed scheme in comparison to the conventional MU-MIMO transmission only scheme.

6.2 Introduction

Both the theoretical and practical understanding have already shown the superiority of MU-MIMO in many cases [56]. Recently, IEEE 802.11ac task group for VHT WLAN is also extending the latest HT WLAN standard with MU-MIMO inclusion. Yet, despite all its superiority, MU-MIMO still have some limitations to contemplate. For instance, each data stream in this scheme is encoded with respect to corresponding node's channel quality. The higher the channel quality is, the higher will be the transmission rate and vice versa. As a result, the network performance is determined by the lowest per-link data rate. If the channel quality between the receiver nodes varies significantly, as shown in Fig. 6.1, MU-MIMO may fail to fully utilize the available MIMO capacity. Similarly, the same problem could arise again due to difference in data length, as shown in Fig. 6.2. Since different applications could have different data lengths and different nodes could have different link qualities, collectively the problem may arise severely. Hence, to leverage this issue and thereby to assist on maximal utilization of the available MIMO capacity, we propose a simple MAC protocol that is based on conventional CSMA/CA, however, works as a hybrid of MU-MIMO and SU-MIMO transmissions. Particularly, we are interested in the forthcoming VHT WLAN, where MU-MIMO transmission will be provisioned between the MIMO nodes in downlink.

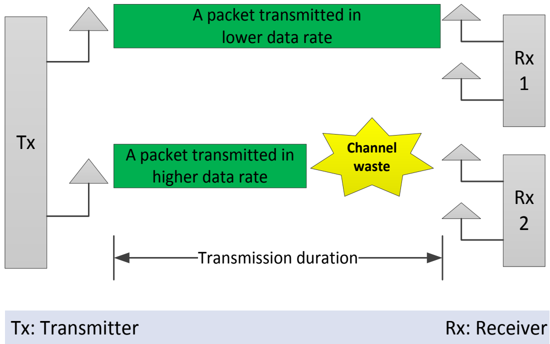


Figure 6.1: Channel waste due to variable link quality in MU-MIMO

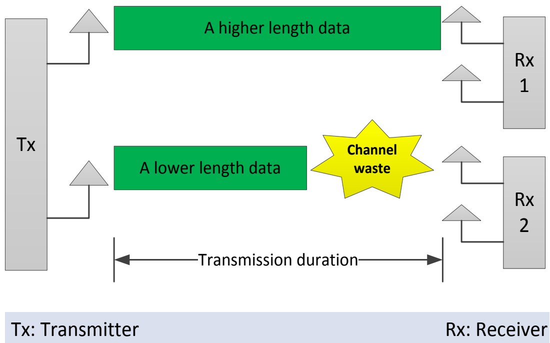


Figure 6.2: Channel waste due to variable data length in MU-MIMO

The proposed protocol acts as a switching entity between MU-MIMO and multiple SU-MIMO (mSU-MIMOs) transmissions. mSU-MIMOs refers here to multiple point-to-point MIMO communication in the same transmission opportunity, i.e. one after another. MAC layer will decide which transmission mode is to follow after analyzing the resulting performance once the control packets are exchanged successfully.

There are some prior works that have also investigated the MAC layer enhancement techniques in MU-MIMO deployed WLANs [57]-[59]. Tandi *et al.* in [57] proposed cross-layer-optimized user grouping strategy so as to optimize the MU-MIMO transmission duration. In this scheme, a primary user is selected at first based on the level of urgency in the data delivery. Then the user group that also includes primary user and has maximum channel capacity is selected as the targeted secondary users for MU-MIMO transmission. Finally, the packet sizes of the secondary users are adjusted to match that of primary user's transmission time by means of fragmentation or aggregation. However, the authors in [57] assume that the CSI of all its receivers are known to the AP ideally, which is not practically implemented without feedback. To implement this scheme, if feedback is provisioned from all of the users, it will incur lots of overhead. While, if limited number of users are selected, the efficiency that could be gained from user selection strategy will be reduced.

Cha *et al.* in [58] presented the performance comparison of downlink user multiplexing schemes in IEEE 802.11ac. [58] has compared the performance of MU-MIMO transmission scheme with downlink frame aggregation scheme. Frame aggregation is similar to mSU-MIMOs, where data packets of multiple users are concatenated and transmitted in one transmission attempt. However, this work is only focused on the performance analysis and had not consider MAC protocol design, control packets modification requirements, modification approaches, and the associated overheads and their effects on the network performance.

In [59], Zhu *et al.* have investigated the problem of downlink MU-MIMO MAC in IEEE 802.11ac in terms of TXOP sharing and have proposed a simple solution to share TXOP among primary Access Class (AC) traffic and secondary ACs traffic. Once any AC (particular data types for a particular receiver) wins a TXOP, it becomes the primary AC. Rest of the ACs (same or other data types for other receivers) then become secondary ACs. Now the duration of the TXOP is determined by the TXOP limit of the primary AC and also the transmission time is determined by the amount of data scheduled to be transmitted by the primary AC. Thus, in this scheme, once the primary AC finishes its transmission, the transmission cycle is ended even if secondary ACs still have packets to send, or the secondary links remain silent if they finished earlier.

In contrast to the aforesaid, this chapter presents a simple yet practicable CSMA/CA based MAC protocol that assists on transmission switching between MU-MIMO and mSU-MIMOs transmission so as to maximize the efficiency of MU-MIMO deployed WLANs. The proposed MAC protocol can be realized only with subtle modifications in conventional MU-MIMO transmission scheme, as will be discussed in the following section.

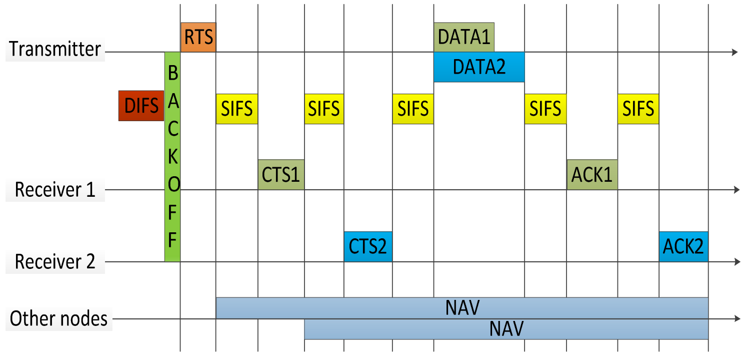


Figure 6.3: MU-MIMO MAC protocol

6.3 Proposed Protocol

6.3.1 MU-MIMO Transmission in VHT WLAN

In multi-user MIMO, a transmitting node transmits X independent parallel data streams from X transmit antenna elements to K nodes, $X \times K$ MU-MIMO system. In draft version of IEEE 802.11ac, it has provisioned MU-MIMO transmission in the downlink of an infrastructured WLANs. Note that while MU-MIMO is often discussed in the context of infrastructured based WLANs downlink, it could conceivably be used in the wireless ad hoc networks as well. In general, as shown in Fig. 6.3, if a node wishes to initiate MU-MIMO transmission, it broadcasts RTS packet to multiple intended receivers by explicitly including their address information serially in the address field. Then the receiver nodes reply with individual CTS packet, also consists of CSI, on the same serial order, however, separated by SIFS. Once the control packet exchange is over, the transmitting node can know about the interference situation in downlink from its accomplished CSIs. With this knowledge, the transmitting node applies interference limited precoding and sends the concurrent data streams. Finally, receiver nodes successfully receiving the data stream acknowledge the reception via ACK packet transmission in same order like CTSs transmission.

6.3.2 Proposed Scheme

In the proposed MAC protocol, as shown in Fig. 6.4, if a node wants to send the data packets to multiple receivers, it acquires the channel by using the same CSMA/CA channel acquisition rule for MU-MIMO as mentioned above. However, once it receives the CTS packets, instead of immediately starting the data transmission it analyzes the resulting performance from MU-MIMO and mSU-MIMOs at first. Since it can know about the channel quality corresponding to each nodes and can figure out the overhead associated with each scheme, it can also figure out the achievable performance from either scheme. Then, whatever scheme is more beneficial, it sends the information to use that scheme by broadcasting a new control packet called new-RTS (RTSn). More importantly, the RTSn plays here a vital role to update NAV for other nodes. According to the supplied information, the transmitting node starts to send the data packets after a SIFS time interval. If it decided to use mSU-MIMOs, it sends data streams in the serial order, one

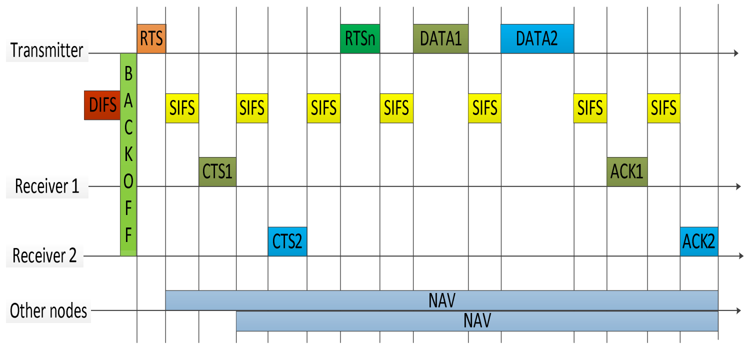


Figure 6.4: mSU-MIMOs MAC protocol

after one, each separated by SIFS. Else, general parallel transmission is followed.

6.4 Numerical Analysis

The carried numerical analysis again follows a modular approach. Firstly, we analyze the behavior of a single tagged node by formulating a single dimensional Markov model as in Chapter 4. With aid of the formulated model, the probability τ that the node starts to transmit in a randomly chosen slot time is calculated. Secondly, we express the average throughput and average packet delay as a function of τ. Some assumptions made for the analysis are as follows: (a) number of nodes in the network are finite (say n), (b) the nodes always have packets to transmit, and (c) the channel is idle. The probability that a node transmits in a randomly chosen slot while employing a default contention resolution algorithm BEB can be derived as in (4.16). Similarly, the collision probability of the transmitted packet can be derived as in (4.17). When these two probabilities are obtained, performance metrics like throughput and delay for the presented scheme can be derived considering other system parameters.

The expressions for throughput and delay are same as the expression for average throughput and delay in Chapter 4. However, the expression for T_s for our investigated approaches in this chapter differs. T_s can be derived as follows.

$$\begin{aligned} T_{s,MU-MIMO} &= T_{DIFS} + T_{RTS} + (2K+1)T_{SIFS} \\ &+ KT_{CTS} + T_{HDR} + T_{E[P]} + KT_{ACK}, \end{aligned} \tag{6.1}$$

$$\begin{aligned} T_{s,mSU-MIMOs} &= T_{DIFS} + T_{RTS} + (3K+1)T_{SIFS} \\ &+ KT_{CTS} + T_{RTSn} + KT_{HDR} \\ &+ KT_{E[P]} + KT_{ACK}, \end{aligned} \tag{6.2}$$

Once the control packets are exchanged successfully, the transmission duration associated with each of the transmission modes can be known easily. Similarly, from that information the total overhead associated with each of the transmission modes could also be computed. Hence, from such computation, as all the other parameters remain constant, the switching criterion can also be designed simply as follows. Let the throughput ratio between two transmission modes is defined

Table 6.1: IEEE 802.11 modulation and coding schemes

MCS index	**Spatial stream**	**Modulation rate**	**Coding rate**	**Data rate**
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

Here data rate is in Mbps and channel bandwidth is 20MHz with gurad band of 800ns.

as,

$$\alpha = \frac{S_{MU-MIMO}}{S_{mSU-MIMO}}, \tag{6.3}$$

such that,

if $\alpha \leq 1$ **then**

$mSU - MIMO$

else

$MU - MIMO$

end if.

In our analysis we will consider a frame aggregation scheme as defined in IEEE 802.11n to indicate about the differences in data lengths. Likewise, in order to indicate the variable link quality, we consider dif-

Frame Control	Duration	K Receiver Address	Transmitter Address	Frame Check
2 bytes	2 bytes	K x 6 bytes	6 bytes	4 bytes

RTS Frame

Frame Control	Duration	Receiver Address	CSI	Frame Check
2 bytes	2 bytes	6 bytes	K bytes	4 bytes

CTS Frame

Frame Control	Duration	K Receiver Address	Transmitter Address	Transmission Mode	Frame Check
2 bytes	2 bytes	2 bytes	K x 6 bytes	1 byte	4 bytes

RTSn Frame

Figure 6.5: Control frames format

ferent MCS as shown in Table 6.1.

6.5 Performance Evaluation and Discussion

We evaluate the performance numerically based on the above presented equations and considering the parameters presented in Table 6.2. The selected parameters are adopted from IEEE 802.11n with subtle modification. The frame format for control packets have been presented in Fig. 6.5. RTS and CTS packets have been modified to append information about the receiver's addresses and CSI, respectively. We assume 2x2 MU-MIMO transmission throughout our analysis. RTSn frame is assumed to append one byte information in addition to RTS frame so as to indicate about the ongoing transmission mode. We consider A-MSDU aggregation scheme with MSDU size fixed to 1500 bytes.

Table 6.2: System parameters considered for performance analysis of MIMO aware MAC for efficient transmission mode selection

Parameters	**Value**
DIFS	34μs
SIFS	16μs
Slot time	9μs
PHY header	40 μs
MAC header	272 bits
RTS packet	208 bits
CTS packet	128 bits
ACK packet	112 bits
RTSn packet	216 bits
Basic data rate	6 Mbps
Minimum contention window (W)	16
Maximum retry limit (R)	6

Average throughput with respect to number of nodes when receiver nodes have different data rates is presented in Fig. 6.6. It can be observed that throughput increases in the beginning when n starts to increase but after reaching a certain threshold it starts to decrease for all range of data rates. This is because when there are only fewer number of nodes in the network the probability of slots remaining idle due to waiting time associated with backoff is high. But, when the number of nodes starts to rise, the throughput increases as the probability of slots remaining idle gets reduced. However, when n increases further, the probability of collision starts to increase which then reduces the throughput. In addition, it can also be observed

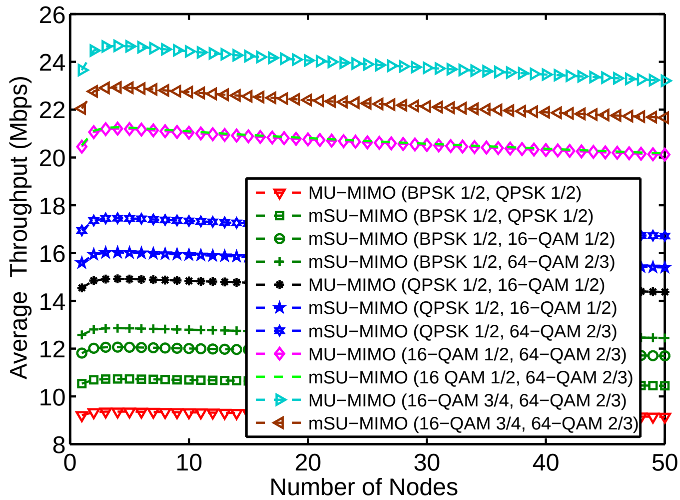


Figure 6.6: Average throughput

that throughput increases on increasing the data rate. It is obvious that increase in data rate decreases the transmission duration which ultimately increases the throughput.

Besides the aforesaid 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), (QPSK 1/2, 64-QAM 2/3), the throughput performance of mSU-MIMOs transmission is higher than that of MU-MIMO. Whereas, for set of MCSs (16-QAM 1/2, 64-QAM 2/3) the throughput performance is comperatively similar. While, for set of MCSs (16-QAM 3/2, 64-QAM 2/3) the throughput performance is lower in mSU-MIMOs than MU-MIMO. These results show the effect of throughput dependency on the lower data rate when we apply MU-MIMO and at the same time it also

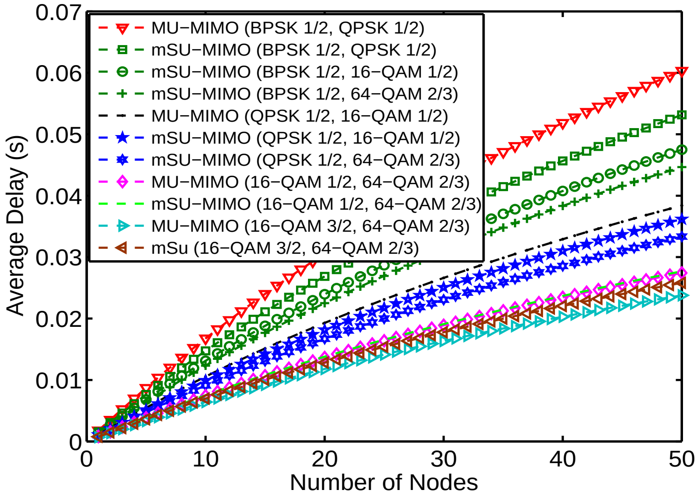


Figure 6.7: Average delay

shows throughput dependency on both the data rates when we apply mSU-MIMOs. From these observations, it is clear that if the resulting transmission duration surpasses the effect of additional overhead in mSU-MIMOs, the overall performance of the system will enhance in comparison to MU-MIMO; otherwise reduce.

Average delay performance for the same network scenario is presented in Fig. 6.7. It can be seen that the delay increases with respect to number of nodes. It is obvious that when number of nodes increases, it increases the collision probability and ultimately the delay. It can also be observed that delay decreases with increase in data rate, as transmission time decreases with increased data rate. Apart from that, in these results as well, the delay for set of MCSs (BPSK 1/2, QPSK 1/2), (BPSK 1/2, 16-QAM 1/2), (BPSK 1/2, 64-QAM

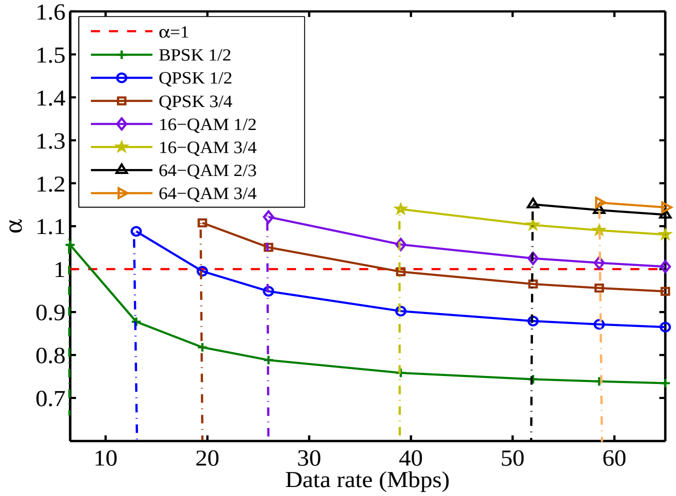


Figure 6.8: Transmission mode selection with respect to link quality

2/3), (QPSK 1/2, 16-QAM 1/2), (QPSK 1/2, 64-QAM 2/3) is lower in mSU-MIMOs. While, for set of MCSs (16-QAM 3/2, 64-QAM 2/3), it is higher. Figure 6.8 shows the criterion for mode change with respect to different MCSs for all range of data rate when we consider the link quality only. While, Fig. 6.9 shows the criterion for mode change considering the link quality as well as data length.

Thus, from the presented analysis, it can be concluded that employing the proposed protocol we can easily establish the switching criterion to achieve more benefits. The transmitting node can easily made a decision on which mode of transmission is to follow after analyzing the resulting performance. The analysis is possible as it could easily gather the required information from the exchanged control packets.

From the presented analysis, it can be concluded that employing

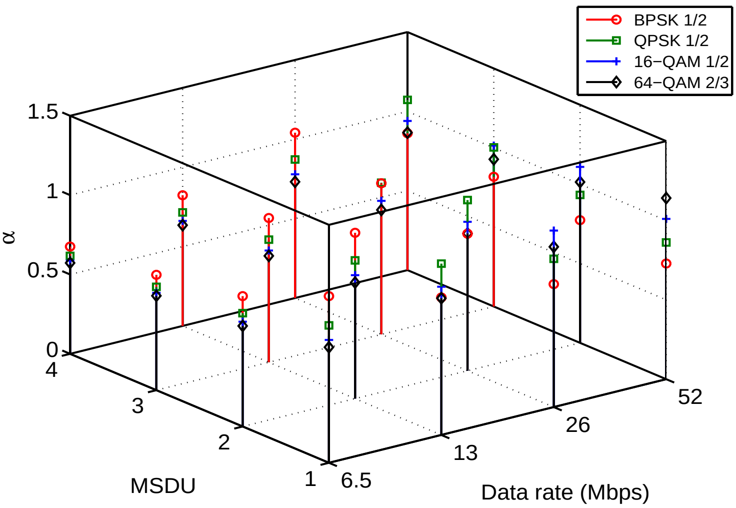


Figure 6.9: Transmission mode selection with respect to link quality and data length

the proposed protocol we can easily establish the switching criterion to achieve more benefits. The transmitting node can easily made a decision on which mode of transmission is to follow after analyzing the resulting performance. The analysis is possible as it could easily gather the required information from the exchanged control packets.

6.6 Concluding Remarks

A scheme to support switching between MU-MIMO and mSU-MIMOs is presented. The proposed scheme is simple and can be realized only with subtle modification in the CSMA/CA protocol. The presented scheme is capable of maximizing the utilization of available MIMO capacity in comparison to fundamental MU-MIMO transmission scheme; when the transmission duration for different receivers varies. Through analytical observations, it is presented that applying the proposed scheme more benefits in terms of throughput and delay could be achieved in comparison to the fundamental MU-MIMO transmission only scheme.

7 Conclusions and Future Work

7.1 Conclusions

In this dissertation, we presented performance analysis of MIMO aware MAC protocols in WLANs and also presented some enhancement techniques. Currently, only SU-MIMO aware MAC protocol is standardized in WLANs (by IEEE 802.11n amendment). Therefore, at first, we presented comprehensive performance analysis of SU-MIMO aware MAC protocol. Then, in second, we analyzed some modification techniques to upgrade SU-MIMO aware MAC protocol into MU-MIMO aware MAC protocols. We presented detailed performance analysis of the upgraded MAC protocols. At last, we presented some enhancement techniques to maximize the utilization of available MIMO capacity in VHT WLAN. In what follows, we summarize the approaches in the order they have appeared in dissertation.

In Chapter 3, we presented achievable performance analysis of the IEEE 802.11n WLAN considering MIMO systems in PHY and enhanced MAC features like frame aggregation, bi-directional data flow, and BACK in MAC layer. We derived expressions for performance metrics like maximum achievable throughput and minimum achievable delay considering all the enhancements features. We showed that throughput linearly increases with number of antenna elements but not with the data rate because of the indispensable overhead associated with MAC protocol. We also showed that bi-directional data flow even cannot leverage linear throughput enhancement. Apart from that, we also showed that there is always a trade-off between spatial multiplexing and spatial diversity, and needs to be optimized carefully. The presented analysis will be helpful to understand tradeoff among the performance of different schemes.

In Chapter 4, along with the discussion on different modification approaches to upgrade SU-MIMO aware MAC into MU-MIMO aware MAC, we provided their detail performance analysis in terms of throughput and delay. Based on analytical modeling and derived expressions, we presented both achievable and average performance analysis. Thus, on one hand, we presented discussion on modification approaches and analytical model to understand their performances, while on the other hand, we also showed the trade-off and limitations of such protocols.

In Chapter 5, we presented a scheme to support MU-MIMO reception in WLANs. On oppose to the MU-MIMO transmission (spatially multiplexed data streams to different receivers in downlink), MU-MIMO reception (spatially multiplexed data streams from different users in uplink) in WLANs is not as easy as the distributed nodes have to initiate their own transmission without negotiation with each other. Therefore, by employing contention based multi-request transmission scheme as a supplementary scheme to the CSMA/CA, we propose this scheme. The proposed scheme is simple and can be realized only with subtle modification in CSMA/CA. Through detail analysis, we presented that provided with optimal parameter set up, MU-MIMO reception with enhanced throughput performance can be achieved with the proposed scheme.

Finally, in Chapter 6, a scheme to support switching between MU-MIMO and mSU-MIMOs is presented. The presented scheme is capable of maximizing the utilization of available MIMO capacity during MU-MIMO transmission when corresponding receivers have different data rates or data lengths. Through analytical observations, it is also presented that applying the proposed scheme more benefits in terms of throughput and delay could be achieved in comparison to the fundamental MU-MIMO transmission scheme as will be provisioned by VHT WLAN.

7.2 Future Work

When upgrading the conventional SU-MIMO protocol to support MU-MIMO transmissions in WLANs, the primary concern is to design a multiple access scheme as we discussed in this dissertation. There can be other supplementary design issues to get additional benefits from such MU-MIMO MACs. For example, network throughput of a MU-MIMO protocol can be enhanced by exploiting multi-user diversity. Similarly, by selecting proper antenna elements, the network throughput can be further enhanced. These issues are possible future works of the dissertation.

Similarly, in the presented enhancement technique in Chapter 5, the node estimation algorithm can be added to make the protocol more dynamic. And, in Chapter 6, we can insert node selection property as a function of SNR or other parameters (e.g. urgency) to further enhance the performance.

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본인이 저작한 위의 저작물에 대하여 다음과 같은 조건아래 조선대학교가 저작물을 이용할 수 있도록 허락하고 동의합니다.

- 다　　음 -

1. 저작물의 DB구축 및 인터넷을 포함한 정보통신망에의 공개를 위한 저작물의 복제, 기억장치에의 저장, 전송 등을 허락함
2. 위의 목적을 위하여 필요한 범위 내에서의 편집・형식상의 변경을 허락함. 다만, 저작물의 내용변경은 금지함.
3. 배포・전송된 저작물의 영리적 목적을 위한 복제, 저장, 전송 등은 금지함.
4. 저작물에 대한 이용기간은 5년으로 하고, 기간종료 3개월 이내에 별도의 의사 표시가 없을 경우에는 저작물의 이용기간을 계속 연장함.
5. 해당 저작물의 저작권을 타인에게 양도하거나 또는 출판을 허락을 하였을 경우에는 1개월 이내에 대학에 이를 통보함.
6. 조선대학교는 저작물의 이용허락 이후 해당 저작물로 인하여 발생하는 타인에 의한 권리 침해에 대하여 일체의 법적 책임을 지지 않음
7. 소속대학의 협정기관에 저작물의 제공 및 인터넷 등 정보통신망을 이용한 저작물의 전송・출력을 허락함.

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