Very High Throughput (VHT) Multi-User Multiple Input Multiple Output (MU-MIMO) Communication in 802.11ac

by

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Abstract

Very High Throughput Multi-User Multiple Input Multiple Output (VHT MU-MIMO) is an 802.11ac communication mode that allows an Access Point (AP) to simultaneously transmit multiple data streams as Aggregated Multi-Protocol Data Units (A-MPDUs) to a group of multiple stations (STAs) over the same channel. This mode combines communication technologies that enable the 802.11ac protocol to use spectrum more efficiently compared to the previous standards. However, VHT MU-MIMO wastes an unused part of the Physical Protocol Data Unit (PPDU) interval when short and long data streams are grouped together.

In this thesis, we propose a solution that improves VHT MU-MIMO communications by reducing wasted portion of the PPDU duration of short data streams by concatenating longer data streams in consecutive groups. Simulations of the VHT MU-MIMO communication process with and without the proposed approach indicate smaller wasted part and shorter transmission time of randomly generated STAs data streams.

Keywords: 802.11ac; Multi-User-Multiple Input Multiple Output; Frame aggregation; Block acknowledgment

Table of Contents

Approval ii
Partial Copyright Licence iii
Abstract iv
Table of Contents v
List of Tables vii
List of Figures viii

Chapter 1. Introduction 1
1.1. History 1
1.2. Classification of Wireless Technologies 1
1.2.1. Personal Area Networks (PANs) 2
1.2.2. Local Area Networks (LANs) 2
1.2.3. Metropolitan Area Networks (MANs) 2
1.2.4. Wide Area Networks (WANs) 2
1.3. IEEE 802 Standards 3
1.3.1. Data Link Layer in 802.11 4
Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) 4
Data Link Frames 5
Management Datagrams 5
Control Datagrams 5
Datagrams of actual data 5
1.3.2. 802.11 Physical Link Layer 6
2.4 GHz 6
5 GHz 6
1.4. IEEE 802.11 Family 7
1.4.1. Legacy IEEE 802.11 7
1.4.2. IEEE 802.11b 7
1.4.3. IEEE 802.11a 8
1.4.4. IEEE 802.11g 8
1.4.5. IEEE 802.11n 8
1.4.6. IEEE 802.11ac 9

Chapter 2. IEEE 802.11ac 10
2.1. Data Link Layer Enhancements 11
2.1.1. Frame Aggregation, Block Acknowledgement (BA), and Reverse Direction Protocol (RDP) 11
2.1.2. Group ID Management Frame 13
2.2. Physical Layer Enhancements 14
2.2.1. Channel Spectrum 14
Channel Width 14
Dynamic Channel Selection 14

Constellation Points in Quadrature Amplitude Modulation (QAM) and Encoding Techniques....15
Multiple Input Multiple Output (MIMO)....15
VHT Sounding Protocol....15
Very High Throughput (VHT) Preamble....19
2.3. Very High Throughput (VHT) Multi–User Multiple Input Multiple Output (MU-MIMO) Communication....21
2.3.1. VHT MU-MIMO Process....21
2.3.2. Drawback Associated to VHT MU-MIMO Communication Process....22

Chapter 3. Concatenation of Long Data Streams in Consecutive Groups....24
3.1. Example of VHT MU-MIMO Communication Process with and without Proposed Enhancement....24
3.2. Proposed Solution for the A-MPDU Size Selection Process....26

Chapter 4. Simulation Results....28

Chapter 5. Conclusion....34

References 36
Appendix A. Simulation Code....38
A.1 Main Function....38
A.2 Data Generator....40
A.3 Assign A-MPDU: Default....41
A.4 Assign A-MPDU: Proposed....42
A.5 Current VHT-MU-MIMO....43
A.6 VHT-MU-MIMO Communication with the Proposed Enhancement....45

List of Tables

Table 2-1. 802.11ac A-MPDU sizes. 12
Table 4-1 Description of Variables used in PPDU duration equation. 29
Table 4-2. Duration of control frames, management frames, and Interframe Spacing....................30

List of Figures

Figure 1-1. Classification of wireless networks based on range of coverage................3

Figure 1-2. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)..4

Figure 1-3. 2.4 GHz spectrum channels. 6

Figure 1-4. 5 GHz spectrum channels before the new channels allocation...................7

Figure 2-1. Frame Aggregation in the Data Link Layer..11

Figure 2-2. Group ID Management Frames. 13

Figure 2-3. A VHT Sounding Process..16

Figure 2-4. Resultant Null Steering..17

Figure 2-5. NDP Announcement Frame...17

Figure 2-6. VHT Compressed Beamforming Action Frame. 18

Figure 2-7. VHT preambles..20

Figure 2-8. Block Acknowledgement in VHT MU-MIMO communication. 22

Figure 3-1. VHT MU-MIMO communication process: (a) Transmission of 6 data streams via VHT MU-MIMO communication process. (b) Transmission of 6 data streams via VHT MU-MIMO communication process with the proposed enhancement.........................25

Figure 3-2. Proposed A-MPDU size selection process. 27

Figure 4-1. Comparison of the proposed approach and the VHT MU-MIMO process..31

Figure 4-2. Performance comparison of 10 simulations: Transmission time...............32

Figure 4-3. Performance comparison of 10 simulations: Number of wasted octets. 32

Figure 4-4. Performance comparison of 10 simulations: Control /Management frames..33

Chapter 1.

Introduction

Wireless Local Area Networks (WLANs) are confined to an area of a single house or office and connects devices wirelessly. WLAN is one of the most influential technologies of the 21st century. Every year, it enables communication in millions of products.

1.1. History

Wireless network communication was first introduced in 1971 by the ALOHAnet that connected computers of two sites through UHF (Ultra High Frequency) channels. Although previous successful attempts used radio transmissions and satellite communications, ALOHAnet was the first technology that introduced freedom of selecting time for transmission and confirmation of received data with an acknowledgement/retransmission scheme [1]. ALOHAnet introduced the method of random access wireless communication that later served as a basis of many standards such as Ethernet, WLANs, GSM, and Satellite communications.

1.2. Classification of Wireless Technologies

Wireless technologies are classified based on coverage and range as:

1.2.1. Personal Area Networks (PANs)

PANs allow consumers to connect devices for personal use that lie within reach of a physical touch. PSN technologies include Bluetooth, Zigbee, Infrared, and Near Field Communication (NFC). This type of communication is usually point-to-point and uses the license free spectrum. Transmission power is limited based on the Federal Communications Commission (FCC) regulations.

1.2.2. Local Area Networks (LANs)

LANs span the area of home/office or a building. They consist of devices sharing the same media channel through various mechanisms. For example, Wireless LANs uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) to sense channel for availability and then transmit. WLAN channels use unlicensed band of the spectrum.

1.2.3. Metropolitan Area Networks (MANs)

MANs span an area of city or a metropolitan region. They consist of cell towers covering certain area and all devices within a tower's range interact with the tower over separate channels or a channel with different digital coding. As a result, there is no overlap of data between multiple devices. Cellular networks are examples of MANs and their communication is performed over a licensed spectrum. MANs have been used since the first commercial radios. Examples of such networks are AM, FM, GSM, LTE, and WiMAX.

1.2.4. Wide Area Networks (WANs)

WANs exist nationwide or expands to scale entire earth [2]. Wireless WANs are extended form of Wireless Metropolitan Networks since those services are provided by cellular and Internet Service Providers (ISPs) nationwide and then connected across the world. Figure 1-1 illustrates ranges of network types classified based on the coverage area.

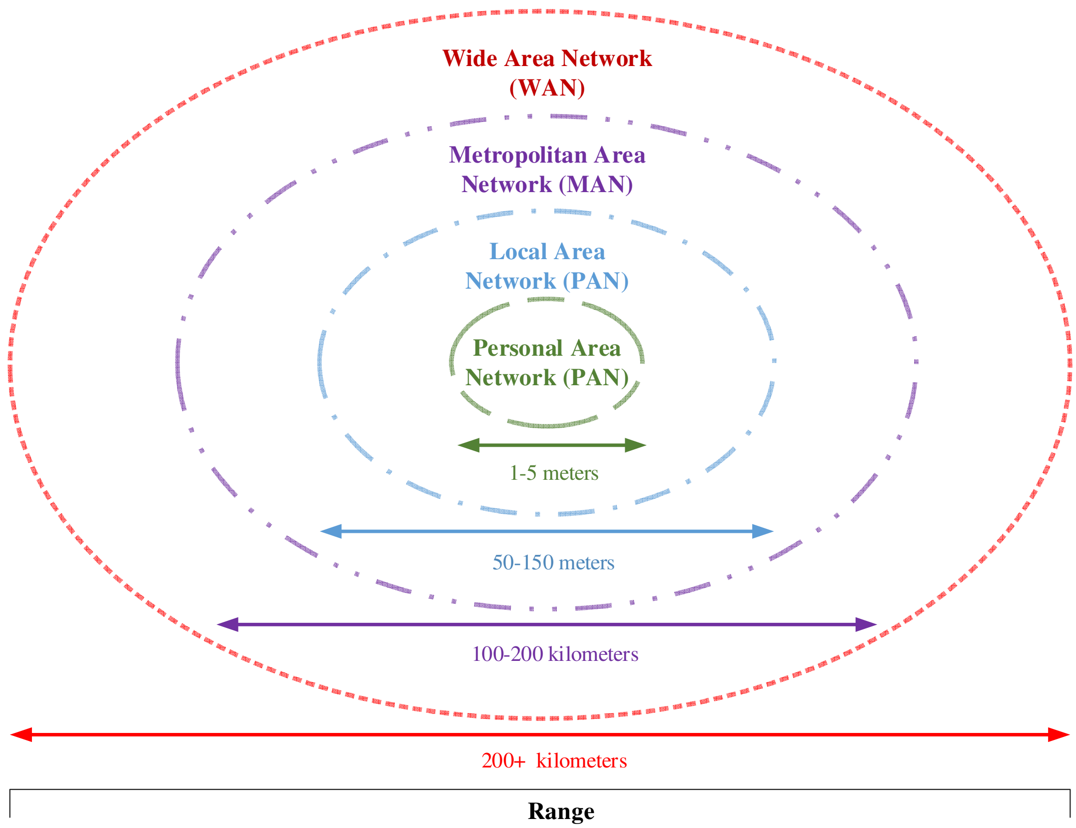


Figure 1-1. Classification of wireless networks based on range of coverage.

1.3. IEEE 802 Standards

IEEE 802 is a family of standards that deals with Local Area Networks (LANs) and Metropolitan Area Networks (MANs). The standards family is an alternate solution to cell relay networks where data are transmitted in equal sized cells. In 802 networks, data are carried in variable size frames based on signal power level. The services specified by the 802 standards deal with the Data Link Layer and Physical Layer of OSI (Open System Interconnection). IEEE 802.11 is a set of standard specifications and technologies for implementation and design of WLAN communication systems. The specifications confine to the Data Link and Physical Layers of the OSI model and, hence, the system can communicate with the existing communication technologies that adhere to the OSI model [3].

1.3.1. Data Link Layer in 802.11

Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)

CSMA/CA is an enhanced version of the Carrier Sense Multiple Access with Collision Detection (CSMA/CD) introduced in wired LANs (IEEE 802.3). The reason for the upgrade was inability of CSMA/CD to ensure collision-free air media. Unlike wired media, air (wireless media) is not space-limited. As a result, there are issues such as hidden terminal effect and channel multipath fading that CSMA/CD fails to address. In CSMA/CD, the STAs are connected in hub topology and the availability of channel is on first come first serve basis. An STA senses the channel prior to transmitting data. If it founds the channel idle, the packet is immediately transmitted [3]. Figure 1-2 illustrates the CSMA/CA protocol flow chart.

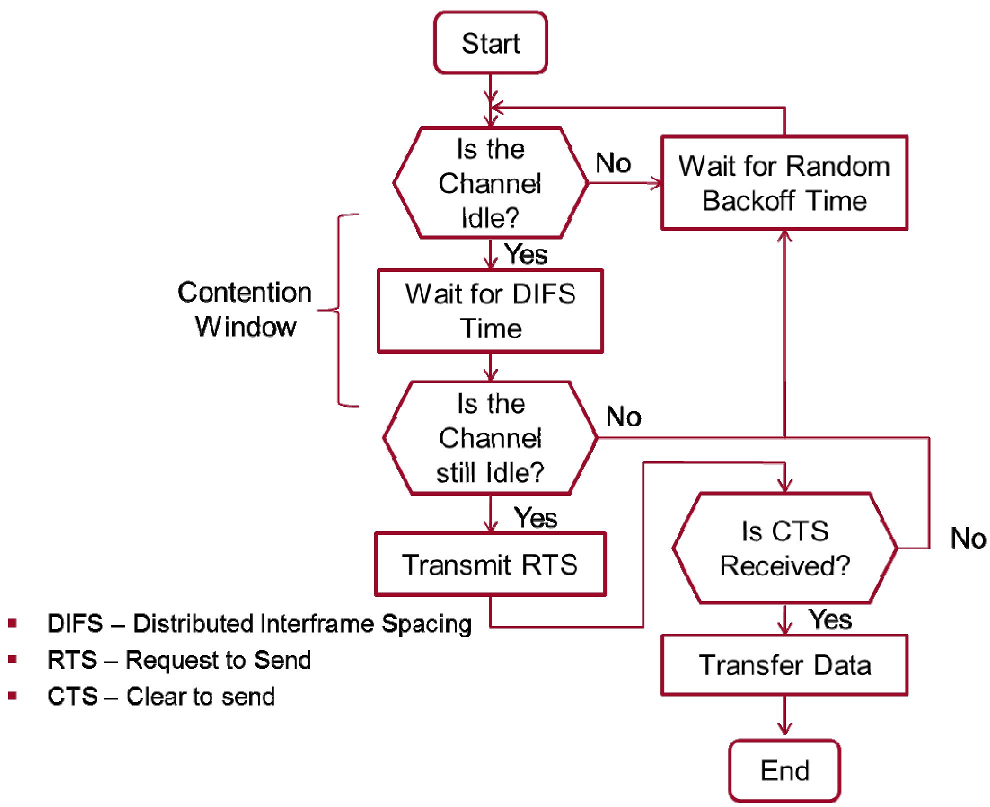


Figure 1-2. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA).

CSMA/CA follows the same approach as CSMA/CD. Before a node transmits data, it first senses the shared media. If channel is busy, the node waits for an exponential back off interval and senses the channel again. On finding the channel idle, it waits again for a period of time called “Distributed Inter Frame Spacing (DIFS)”. This wait period prevents collision when multiple nodes attempt to transmit at the same time as soon as they sense an idle channel. The duration of DIFS is randomly selected from the range of values defined by the Contention Window (CW). After the DIFS period, if channel is idle again, a Request to Send (RTS) frame is sent to the receiver node to ensure that no hidden node problem occurs [3]. On receiving RTS and observing an idle channel, the receiver node replies with a Clear to Send (CTS) frame broadcasted to all nodes that channel will be busy for a specified amount of time. The transmitting node sends the desired data to the receiver. The receiver responds with the ACK that a successful transmission has been achieved.

Data Link Frames

802.11 WLAN frames are called datagrams. There are three types of datagrams and each datagram contains distinct headers.

Management Datagrams

These frames contribute to the establishment and maintenance of a communication process. They include Authentication, Association, Disassociation, De-authentication, Beacon, Probe, and Re-Association datagrams.

Control Datagrams

These frames facilitate exchange of data between stations. Examples of such frames are Acknowledgement, CTS (Clear To Send), and RTS (Request To Send).

Datagrams of actual data

These frames contain actual data sent by nodes. Their headers are enhanced to enable transmission of frames over wired and wireless networks.

1.3.2. 802.11 Physical Link Layer

802.11 commonly employs two frequency bands for communications. These bands are license free. There is a limit on active power that is regulated and restricted by FCC specifications. Active power is the transmission power available to the device circuitry.

2.4 GHz Spectrum

The 2.4 GHz band provides 83 MHz of total contiguous bandwidth, spanning from 2.4 GHz to 2.483 GHz. In this band, fourteen 22 MHz channels are formed where two consecutive channels are 5 MHz apart. Figure 1-3 illustrates fourteen channels and commonly used three non-overlapping channels of the 2.4 GHz spectrum.

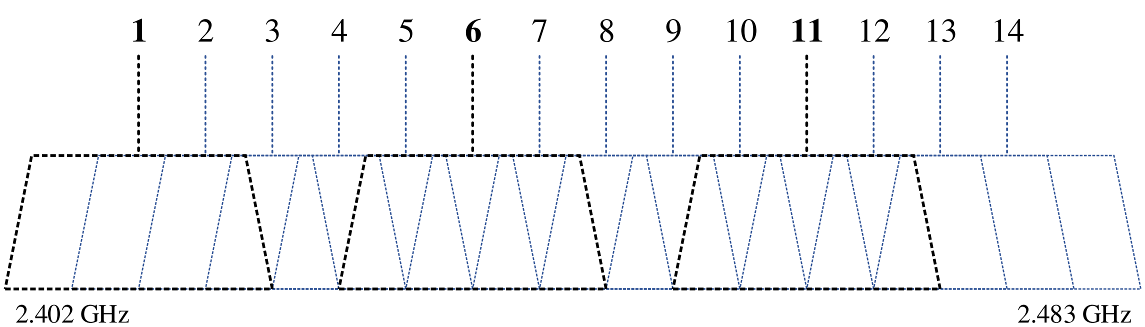


Figure 1-3. 2.4 GHz spectrum channels.

5 GHz Spectrum

In WLANs, 5 GHz was previously divided into two spectrums: lower spectrum (5.150 GHz to 5.35 GHz) and higher spectrum (5.75 GHz to 5.825 GHz). These channel spectrums are illustrated in Figure. 1-4. Recently, the 5 GHz frequency band has been introduced with new non-overlapping channels by extending the spectrum of unlicensed free band. The FCC reclaimed some of the WLAN spectrum missing channels that interfered with the Terminal-Area Doppler Weather Radars (TDWR). The FCC also allocated two new bands of 195 MHz of spectrum for wireless LANs. As a result, WLANs now have allocated full spectrum from 5.150 GHz to 5.925 GHz [4].

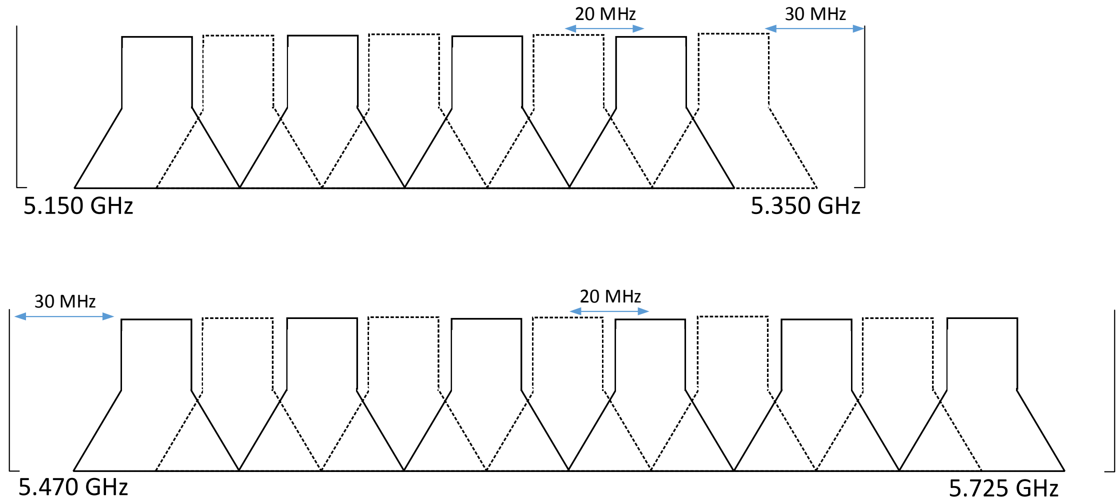


Figure 1-4. **5 GHz spectrum channels before the new channels allocation.**

1.4. IEEE 802.11 Family

The 802.11 family includes over-the-air modulation techniques that follow the same basic protocol. Legacy 802.11 was the first wireless standard followed by 802.11a and 802.11b. 802.11b was the first standard to be widely adopted, followed by 802.11g. 802.11n and 802.11ac are the latest multi-streaming modulation standards that offer evolutionary improvements over their predecessors.

1.4.1. Legacy IEEE 802.11

The first 802.11 version was released in 1997 and enhances in 1999 [3]. It supports data rates of 1 Mbps and 2 Mbps, transmitted as IR signals, Frequency Hopping Spread Spectrum (FHSS), or Direct Sequence Spread Spectrum (DSSS) at 2.4 GHz on a 20 MHz wide channel.

1.4.2. IEEE 802.11b

IEEE 802.11b is an extension of the IEEE 802.11 DSSS scheme. It provides data rates of 5.5 Mbps and 11 Mbps. It was introduced in October 1999. Each channel requires the same 20 MHz bandwidth as in case of the 802.11 DSSS. To achieve a higher data rate within the same bandwidth, the standard employs a modulation scheme called Complementary Code Keying (CCK). In CCK we have shorter chip sequence then the DSSS 11 bit Barker code. Hence less spreading to obtain higher data rate but more susceptible to narrowband interference resulting in shorter radio transmission range [6]. 802.11b operates at 1 Mbps, 2 Mbps, 5.5 Mbps, and 11 Mbps. 802.11b achieved market success because of its long range and stable connectivity.

1.4.3. IEEE 802.11a

802.11a, released in October 1999, uses OFDM (Orthogonal Frequency Division Multiplexing) where multiple carrier signals carry multiple data. 802.11a data rates are 6 Mbps, 9 Mbps, 12 Mbps, 18 Mbps, 24 Mbps, 36 Mbps, 48 Mbps, and 54 Mbps. The standard persuaded consumers to upgrade to the 5 GHz frequency spectrum, which is less consumed by various wireless devices compared to 2.4 GHz. However, the standard was not successful.

1.4.4. IEEE 802.11g

IEEE 802.11g, introduced in 2003, uses the same OFDM technology as 802.11a at the 2.4 GHz frequency band. It could achieve a maximum data throughput of 54 Mbps. It was backward compatible with 802.11b. Hence, the consumer market could easily migrate to the new technology. 802.11g supported data rates of 1 Mbps, 2 Mbps, 5.5 Mbps, and 11 Mbps using DSSS and 6 Mbps, 9 Mbps, 12 Mbps, 18 Mbps, 24 Mbps, 36 Mbps, 48 Mbps, and 54 Mbps using OFDM.

1.4.5. IEEE 802.11n

The 802.11n was first introduced in 2009 in order to compete with wired LANs and address the industry demands for excessive traffic in LANs. In October 2011, the final draft with the latest amendments was presented, where Multiple Input Multiple

Output (MIMO) technology combined with the OFDM technology was introduced. Hence, one, two, three, or four spatial streams are transmitted over same channel enabling significantly higher data rates. Moreover, it has flexibility to operate on both 20 MHz and 40 MHz channel widths. 802.11n operates at 2.4 GHz and 5 GHz. Hence, 802.11n is backward compatible with 802.11a/b/g. For different spatial streams, different data rates are available. The overall maximum possible bit rate is 600 Mbps at 40 MHz channel width. 892.11n has a special communication mode call High Throughput (HT) communication where multiple spatial streams are simultaneously transmitted to the same STA over the same channel width.

1.4.6. IEEE 802.11ac

In 2013, IEEE published 802.11ac as a new standard that aims to achieve throughput of Gbps on a channel 20 MHz wide. This standard, unlike others, calls for technological limits on the Physical and Data Link Layers and pursues enhancements in technologies such as channel width, OFDM symbols, preambles, modulation schemes, encoding techniques, channel assignment, acknowledgement of data frames, channel assessment, and frames aggregation. 802.11ac also specifies an explicit beamforming mechanism as a standard that enhances the MIMO systems and introduces a special communication mode called Very High Throughput (VHT) communication.

Chapter 2.

IEEE 802.11ac

In 2007, IEEE 802.11 working group began focusing on the 802.11n standard and discovered the potential of technologies such as aggregated channel width, MIMO, and support for 2.4/5GHz. However, they failed to introduce a standard protocol for Beamforming. Furthermore, increasing demand for throughput from industry indicated that WLANs should provide Gbps throughput and compete with wired LANs. Hence, two Project Authorizations (PARs) were established: 802.11ac for under 60 GHz and 802.11ad for over 60 GHz frequency band. The 802.11ac task group was established in November 2008. In December 2013, it published its approved amendment. One of the notable enhancements is the APs capability to communicate in downlink with multiple STAs simultaneously over the same channel width. This process is called Very High Throughput Multi-User Multiple Input Multiple Output (VHT MU-MIMO) communication mode. It is made possible by multiple enhanced technologies introduced in 802.11ac.

Listed here are technologies that have been upgraded in 802.11ac and have contributed in enhancing its throughput. These enhancements also enable devices to communicate using the VHT MU-MIMO mode.

2.1. Data Link Layer Enhancements

2.1.1. Frame Aggregation, Block Acknowledgement (BA), and Reverse Direction Protocol (RDP)

On Data Link Layer, 802.11n introduces frame aggregation that allows faster transmission of additional data compared to previous standards. Traditionally, in wireless LANs, the stream of communicated data is captured up to one frame at a time over the channel. Hence, the ratio of frame overhead to data payload occupying the channel is not very effective. Frame aggregation is proposed to accumulate multiple frames of payload with one time overhead to traverse the channel. Frame aggregation is done at two levels as illustrated in Figure 2-1.

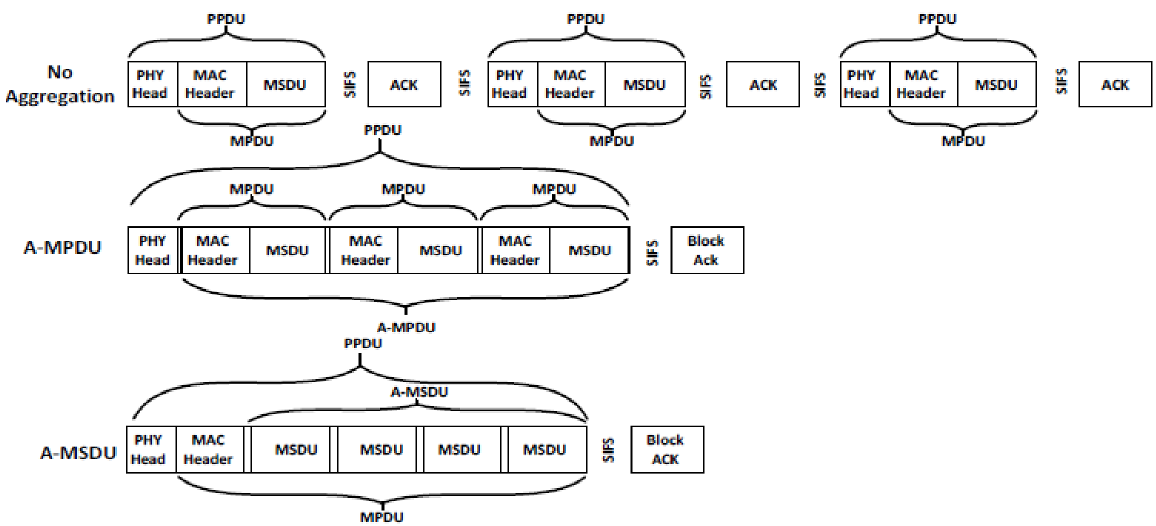


Figure 2-1. Frame Aggregation in the Data Link Layer.

Aggregated Multi Service Data Unit (A-MSDU) is aggregation at the Logical Link Control (LLC) sub-layer of the Data Link Layer. In A-MSDU, un-framed packets are aggregated and header and trailer are added forming one A-MSDU. This one A-MSDU unit is then handed to the lower layers for transmission. In A-MSDU, the intended packets are from the same source and intended to the same destination. These are data frames only and no management or control frames may join the aggregation. Since there is one trailer, a Cyclic Redundancy Check (CRC) is executed once over the aggregated frames. In the case of an error in any frame, the aggregated frames have to be retransmitted. Excessive overhead is significantly reduced in A-MSDU. However, the system is more prone to errors, causing retransmissions.

Aggregated Multi-Protocol Data Unit (A-MPDU) is aggregation at the Media Access Control (MAC) sub-layer of the Data Link Layer. In A-MPDU, actual frames are aggregated and then handed to the lower layer. A-MPDU introduces benefit of aggregating multiple frame types and frames from different sources to the intended destination. Since each frame has its own CRC at the trailer, an error in frame implies that only the individual frame is retransmitted. Overhead is comprised not only of the headers and trailers at the Data Link Layer, but also of the A-MPDU delimiter bits per MPDU. Moreover, a combination of AMPDU and A-MSDU may also be used, leading to optimal results. In 802.11ac, only A-MPDU is used. In 802.11n, the maximum A-MPDU size is 11,454 octets and its use is very limited because its usage in a normal consumer environment hasn't been tested. In 802.11ac, the maximum A-MPDU size is 1,048,575 octets and every frame transmitted is aggregated. Available A-MPDU sizes in 802.11ac are listed in Table 2-1.

Serial No.	A-MPDU sizes (octets)
1	8,191
2	16,383
3	32,767
4	65,535
5	131,071
6	262,147
7	524,287
8	1,048,575

Table 2-1. 802.11ac A-MPDU sizes.

Block Acknowledgement (BA) frame acknowledges all frames successfully received within an A-MPDU. BA may immediate or delayed. Immediate BA is the acknowledgment request that transmitter expects soon after a Short Inter-frame Spacing (SIFS) of a transmitted data. Delayed BA is sent later by the receiver. The reverse direction protocol (RDP) plays an important role for immediate BA. Through RDP, the data transmitting STA signals to the intended recipient to send BA after a Short Interframe Spacing (SIFS) within its TXOP (Transmit Opportunity) duration.

2.1.2. Group ID Management Frame

Special frames are introduced in 802.11ac to assign Group ID and User Position ID to STAs. These IDs are assigned to the destination STAs in the VHT MU-MIMO communication mode. All destination STAs where data are intended to be transmitted simultaneously in the downlink by an AP, are assigned a Group ID. Per Group ID, every STA is assigned a unique User Position ID. An STA may be assigned multiple Group IDs. However, the User Position ID is unique within the group. Assignment of Group IDs is communicated to STAs via the "Group ID Management Frame" using the Action frame format shown in Figure 2-2.

	Category	VHT Action	Membership Status Array	User Position Array
Octets:	1	1	8	16

Category: Action frame category is VHT. (Value: 00001101)

VHT Action: Group ID Management (Value: 00000001)

Membership Status Array: Group ID assigned

User Position Array: User Position assigned within the group ID.

Figure 2-2. Group ID Management Frames.

Each bit in the eight octets of the Membership Status Array indicates one group among 64 Group IDs. The first Group ID (0) and the last Group ID (63) are used for SU transmission while Group IDs 1 to 62 are assigned to STAs for VHT MU-MIMO communication. Membership Status Array field is followed by the User Position Array of 16 octets. A pair of bits of this field coincides with a single bit of Membership Status Array field. Thus, within one group, four combinations of User Position Array may be created. They are assigned to different STAs. These STAs then communicate using MU-MIMO communication.

2.2. Physical Layer Enhancements

2.2.1. Channel Spectrum

802.11ac only operates at 5 GHz. This was a very bold decision to completely migrate from the previous standards operating frequency of 2.4 GHz and leave no possibility for backward compatibility with most deployed IEEE 802.11b/g standards. 802.11n partially uses 5 GHz and it is backward compatible with 2.4 GHz. Compared to 2.4 GHz, 5 GHz has less interference and, hence, signal strength is stable. Previous attempts to transition to the 5 GHz band were made in 1999 by the IEEE 802.11a standard. However, it failed because the standard was not widely acceptance in the industry [8]. 802.11ac has many attractions due to smart technologies it includes. Hence, its acceptance chances are very high. Furthermore, FCC has introduced many new non-overlapping channels for 802.11ac by extending the spectrum of unlicensed free band (Section 1.3.2.2).

Channel Width

20 MHz is a constant channel width in all 802.11 standards. 802.11n introduces channel width of 40 MHz for optional use. 802.11ac extends the channel width concept and introduces flexible channel widths of 20 MHz, 40 MHz, 80 MHz, 160 MHz, and 80+80 MHz (non-alternate channels). Increasing the channel width leads to higher throughput as additional OFDM symbols are transmitted.

Dynamic Channel Selection

In 802.11ac, the primary channel and channel width change on frame-to-frame basis. Thus, the available channel width is utilized in a very effective way accommodating more data to transmit instantaneously. In previous standards, the primary channel was selected manually.

Constellation Points in Quadrature Amplitude Modulation (QAM) and Encoding Techniques

In WLAN 802.11a/g/n standards, Quadrature Amplitude Modulation (QAM) is performed for constellation points of 4, 16, and 64 transmitting 2, 4, and 6 bits per OFDM symbol, respectively [3]. All these standards use Block Convolutional Codes (BCC). 802.11ac introduces 256-QAM constellation that accommodates 8 bits in an OFDM symbol. Due to large number of combinations, 256 QAM is more prone to errors. Hence, Low Density Parity Check (LDPC) encoding is suggested along legacy BCC leading to 1-2 dB gain at receiver STAs [4].

Multiple Input Multiple Output (MIMO)

802.11n standard introduces MIMO systems in WLANs. In 802.11n, an AP may have maximum 4 antennas [4]. An AP may use all antennas and transmit maximum of up to 4 data streams to an STA achieving high throughput over the same channel width. 802.11ac enhances this communication with maximum of 8 data streams. This implies that an AP may have maximum 8 antennas in 802.11ac. 802.11ac standard also introduces a new communication mode using MIMO technology called Multi-User MIMO communication [4]. It allows an AP to transmit data to multiple STAs simultaneously over the same channel width.

VHT Sounding Protocol

802.11ac uses VHT sounding protocol, an explicit beamfroming mechanism where a beamformer sends a NDP (Null Data Packet) to beamformee. The beamformee receives the NDP and creates a steering feedback “V” and sends it to a beamformer. It is used by beamformer to prepare steering matrix “Q”. VHT Sounding protocol ensures that it successfully manages reception of feedback one by one after performing feedback poll for “n” designated STAs. This process is illustrated in Figure 2-3.

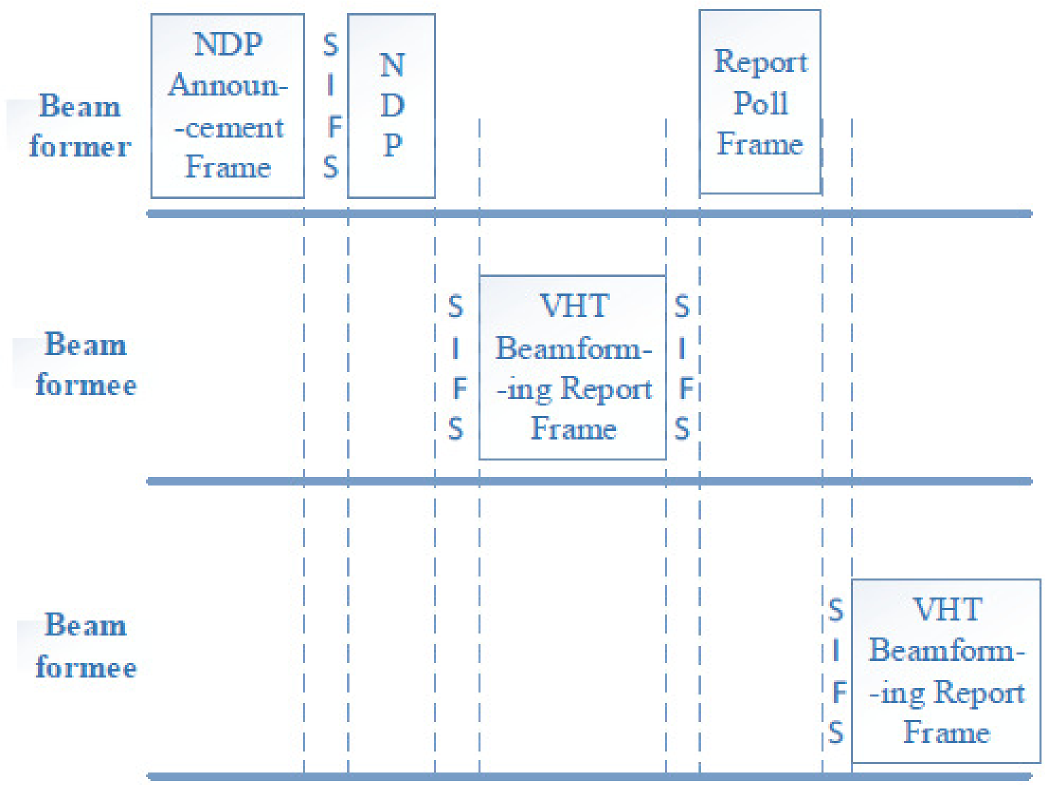


Figure 2-3. VHT Sounding Process.

The VHT Sounding process illustrated in Figure 2-3 contains different type of frames that are signaled between beamformer and beamformee in order to create a steering matrix [4], [7]. The steering matrix not only provides steering of particular space-time streams in particular STA's direction but also nullifies the streams of other STAs. This significantly helps the VHT MU-MIMO communication process, as shown in Figure 2-4. VHT sounding protocol ensures that for "n" STA's listed in the field, it successfully manages reception of feedback one by one after feedback poll as given. In case that any STA is left, its report may be sent later or may be fragmented to transmit a portion before TXOP expires.

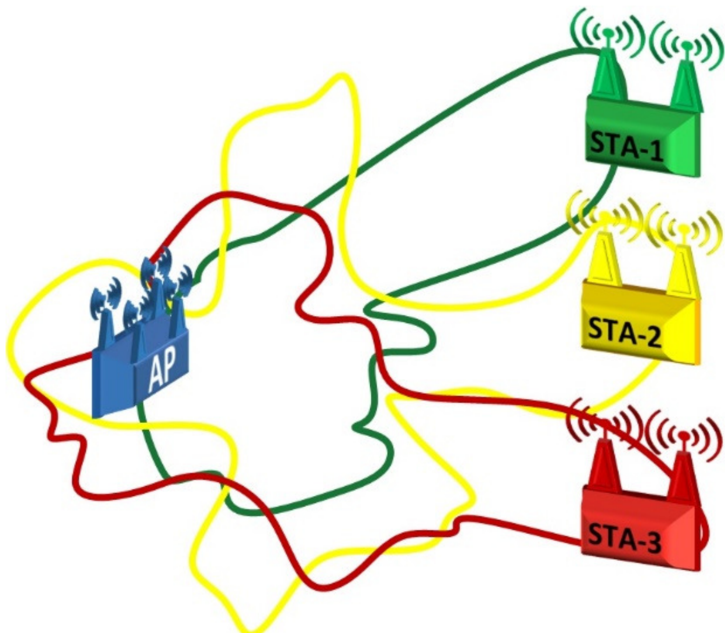
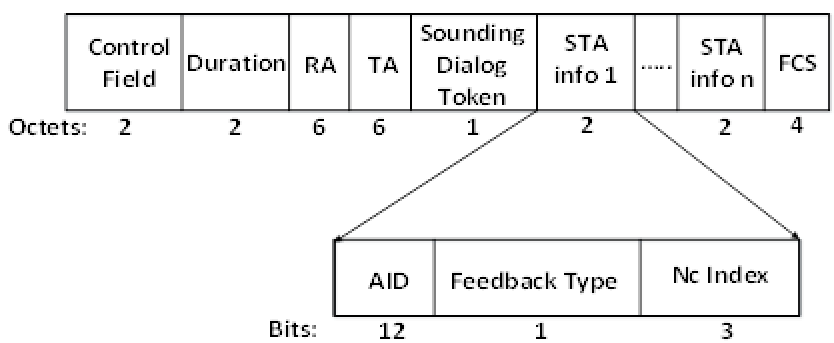


Figure 2-4. Resultant Null Steering.

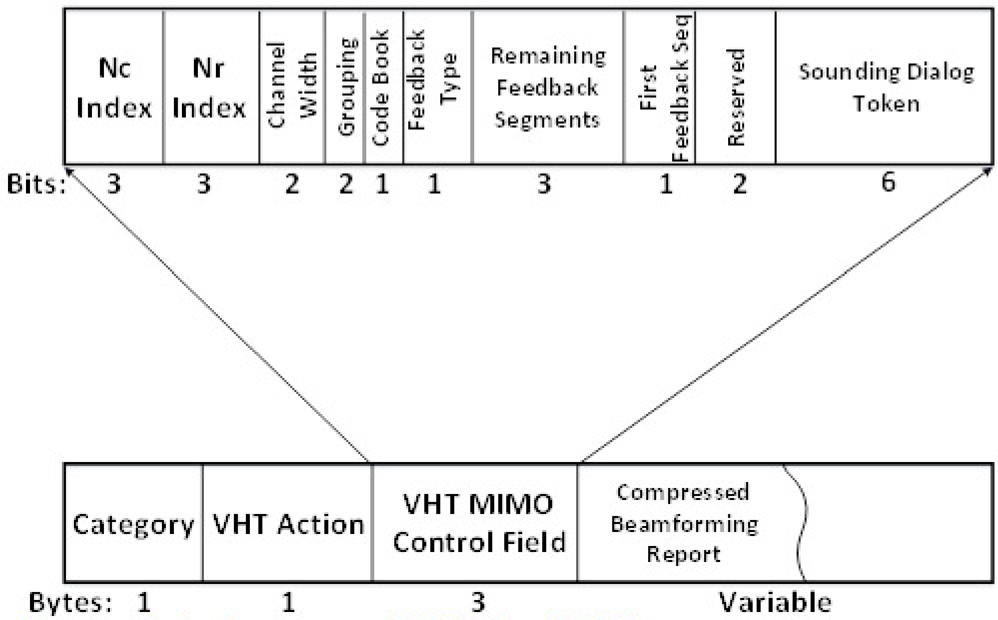
An AP in its Transmit Opportunity (TXOP) broadcasts an NDP Announcement control frame towards the intended STAs. Fields and values of this frame for MU communication are shown in Figure 2-5.



Control Field: Control frame type (VHT NDP Announcement Frame) (value 10101000)
Duration: The interval over which the TXOP is valid in µs
RA: Recipient MAC Address (broadcast address in the MU case)
TA: Transmitters Address. (AP's MAC Address)
Sounding Dialog Token: Token ID unique to this session
STA info-1:
AID: STA's unique ID
Feedback Type: either SU or MU
Nc Index: Number of STS intended to the STA by AP
FCS: For CRC codes.

Figure 2-5. NDP Announcement Frame.

In the VHT sounding process, NDP Announcement frame is transmitted first followed by NDP (Null Data Packet). A NDP is a Physical Protocol Data Unit (PPDU) without data field. On receiving the NDP, the beamformee (STAs) calculates the feedback beamforming matrix "V" and responds with a VHT Compressed Beamforming Action frame that has multiple sub-frames/ fields, as shown in Figure 2-6.



Category: Action frame category is VHT (value: 00001101)
VHT Action: VHT compressed beamforming (value: 00000000)
VHT MIMO Control Field:
Nc Index: Number of columns (i.e., number of STS).-
Nr Index: Number of rows (number of reception antennas).-
Channel Width: 2 bits indicating 20, 40, 80, 160 MHz
Grouping: Indicating subcarrier grouping, value: {0,1,2}, Ng:{1,2,4}
Code Book: On feedback=1 indicate MU. Hence:

	0	1
Ψ	5 bits	7 bits
Φ	7 bits	9 bits

Feedback Type: Either SU(0) or MU(1)
Remaining Feedback Segment: Related to fragmentation
Reserved: Reserved
Sounding Dialog Token: Token ID unique to this session.

Figure 2-6. VHT Compressed Beamforming Action Frame.

VHT MIMO Control Field is the first field of this frame. The second field is VHT Compressed Beamforming Information Report Field that explicitly carries beamforming feedback information in form of matrix "V" that comprises of angles and average SNR value of space-time streams. This information is used by beamformer to create the steering matrix “Q”. The length and width of VHT compressed beamforming information report field vary depending on: 1. Nr (Number of receiver antennas) and Nc (Number of STS’s) as provided in the VHT MIMO Control field; 2. The order of angles that are being included in quantized form per subcarrier (Ns: 312.5 kHz OFDM symbol or subcarriers). It implies different number of subcarriers (Ns) depending on the channel width. The number of bits indicating the angles of subcarriers varies. Finally, the number of subcarriers is reduced by grouping the adjacent subcarriers. The number of subcarriers that are grouped together are indicated by variable “Ng”. This information, called compressed feedback report, is transmitted to the AP. Average SNR is an 8-bit field calculated as a 2’s complement integer. This field stores calculated average SNR in decibels of each column of Nc (space-time stream).

Very High Throughput (VHT) Preamble

802.11ac employs mixed mode format preamble only, unlike 802.11n that introduces a newer Greenfield preamble. The mixed mode format preamble maintains the legacy preamble portion to resolve compatibility issues while the new VHT preamble portion is specifically enhanced to accommodate transmission of multiple streams to multiple users over the channel. VHT preamble also accommodates eight space-time streams of single STA, unlike 802.11n HT preamble that supported only four. VHT preamble has two signaling fields: VHT SIG-A and VHT SIG-B. VHT SIG-A is 48-bit in length and it is transmitted as common signaling field transmitted toward all STAs of a group for MU transmission. VHT SIG-A is divided into two parts: VHT SIG-A1 and VHT SIG-A2. Both are shown in Figure 2-7.

VHT SIG-B follows the VHT SIG-A signaling field. Unlike VHT SIG-A, this field is not transmitted to all STAs as one common block. Instead, multiple VHT SIG-Bs are propagated in the direction of STAs. VHT SIG-B direction of propagation is chosen according to the steering matrix prepared by AP. This signaling field has two responsibilities: 1. MCS subfield identifies the MCS value of an STS in an MU STA;

VHT SIG-A1

24 Bits

Channel Bandwidth	Reserved	STBC	Group ID	MU[0] NSTS	MU[1] NSTS	MU[2] NSTS	MU[3] NSTS	TXOP_NOT_ALLOWED BIT	Reserved
Bits 2	1	1	6	3	3	3	3	1	1

Channel Bandwidth: Channel width 20, 40, 80 or 160 MHz
Reserved: Reserved
STBC: No STBC in MU case (hence, it is set to 0)
Group ID: Indicate the group ID for which the STA is intended
MU[0] NSTS: Indicate the STS of STA with User position ID 00
MU[1] NSTS: Indicate the STS of STA with User position ID 01
MU[2] NSTS: Indicate the STS of STA with User position ID 10
MU[3] NSTS: Indicate the STS of STA with User position ID 11
TXOP_NOT_ALLOWED: Related to power saving
Reserved: Reserved.

VHT SIG-A2

24 Bits

Short GI	Short NSYM Disambiguation	MU[0] Coding	LDPC Extra OFDM Symbol	MU[1] Coding	MU[2] Coding	MU[3] Coding	Reserved	Reserved	Reserved	CRC	Tail
Bits 1	1	1	1	1	1	1	1	1	1	8	6

Short GI: Indicates Short Guard Interval usage
Short NSYM Disambiguation: Relates to Short GI and N_{SYM}
MU[0] coding: Indicates BCC(0) and LDPC(1) for STA with user position 00
LDPC Extra OFDM Symbol: Indicates existence of extra OFDM symbols in LDPC coding
MU[1] coding: Indicates BCC(0) & LDPC(1) for STA with user position 01
MU[2] coding: Indicates BCC(0) & LDPC(1) for STA with user position 10
MU[3] coding: Indicates BCC(0) & LDPC(1) for STA with user position 11
Reserved: Reserved
Reserved: Reserved
Reserved: Reserved
CRC: For CRC codes
Tail: Used to terminate convolutional encoder of VHT Sig-A field.

Figure 2-7. VHT preambles.

2. The VHT A-MPDU length field stores length of A-MPDU data in 4-octet chunks. It informs STAs to turn off their radios to save power once the specified A-MPDU size is collected. The remaining MPDUs are null MPDUs that are placed to fill up the A-MPDU [7]. The length of VHT SIG-B field varies for different channel widths because extra bits are required by the VHT A-MPDU length field.

2.3. Very High Throughput (VHT) Multi–User Multiple Input Multiple Output (MU-MIMO) Communication

802.11n enhanced robustness of WLAN communications through MIMO technology by introducing High Throughput (HT) mode where an AP that takes advantage of space diversity might simultaneously transmit multiple data streams on the same channel to a single STA. VHT more efficiently uses spatial diversity by allowing multi-stream transmission from AP to multiple STAs. Maximum of four STAs may communicate simultaneously. The successful extraction of their own streams by STAs is the result of beamforming where space-time streams of a particular STA are directed toward the STA and streams of other STAs are nullified in its direction.

2.3.1. VHT MU-MIMO Process

Consider an AP that wishes to transmit data in downlink to multiple STAs. The AP calculates the steering matrix “Q” for successive transmissions. 802.11ac uses explicit NDP sounding process to collect steering feedback of the STAs. For VHT sounding process, an AP allocates a TXOP and broadcasts an NDP announcement frame with concerned STAs information in the Info field. Following the NDP announcement frame, a NDP (non-data PPDU) is transmitted. This NDP is used by STAs to calculate their beamforming feedback information “V” [4]. The STAs respond to AP with a VHT Compressed Beamforming Report (CBR) frame, which has all the necessary information in subfields of control frame shown in Figure 2-6. After collecting the individual STAs (CBR) frames, AP uses the information from frames to create a steering matrix “Q”. AP assigns a single Group ID to the STAs and within Group ID assigns them a unique User Position ID. This information is transmitted to the selected STAs through the Group ID management frame. AP starts aggregating frames of the respective STAs and for each space-time stream (STS), selects one of the A-MPDU size from Table 1. In a VHT group, the STS with the longest PPDU duration specifies the PPDU duration of the entire group. All the data streams that have insufficient data MPDUs to fill up the entire PPDU duration are filled with null MPDUs.

A PPDU is formed for all data streams by insertion of preambles. The VHT SIG-A preamble that follows the legacy preamble is transmitted to all STAs as a single common block. An STA that has the same Group ID as indicated in transmitted VHT-SIG-A, will further inspect the MU-NSTS field of VHT SIG-A to determine how many space-time streams are directed towards the User Position ID assigned to it. VHT training fields follow the VHT SIG-A. After VHT training fields, the steering matrix-based directed transmissions begin. First, the VHT SIG-Bs are sent as a preamble and carries signaling information for specific STA such as modulation and coding scheme and length of A-MPDU. After VHT-SIG-B, A-MPDUs of STAs are transmitted. All the STAs A-MPDUs are alternatively block acknowledged after certain interval of data streaming. There is an implicit Block Acknowledge Request for each STA, as shown in Figure 2-8.

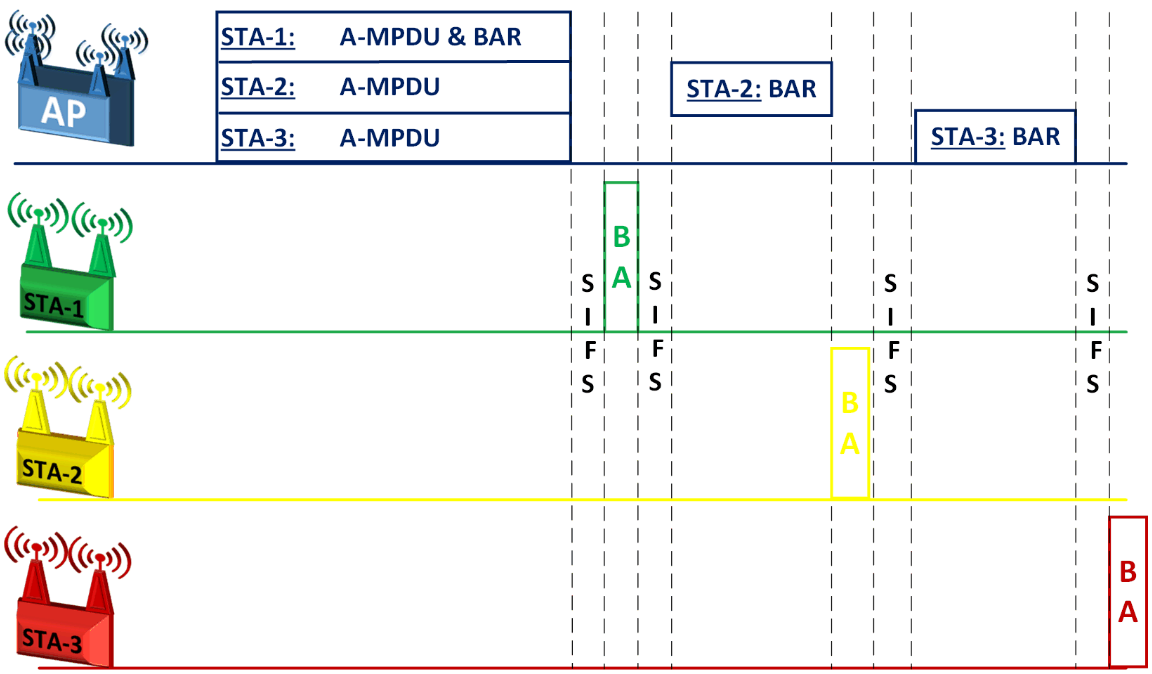


Figure 2-8. **Block Acknowledgement in VHT MU-MIMO communication.**

2.3.2. Drawback Associated to VHT MU-MIMO Communication Process

In VHT MU-MIMO communication, a data stream with the longest PPDU duration decides the PPDU duration of the entire group and the remaining short data streams have to fill up the PPDU duration with null MPDUs once their data MPDUs are utilized. Hence, the portions of short data streams are wasted since there are no data to transmit over the channel allocated to the group. This occurrence of unused portion of short data stream due to transmission of data streams of unequal PPDU durations has been already recognized [9], [10]. The transmission time of the STAs data stream may be similar if the longer data stream has transmission throughput with a higher MCS index. Other data streams also have the MCS index proportional to their length. In the worst case, this may lead to inferior transmission time if STA with long data streams has large amount of data to send while having transmission throughput with a lower MCS index.

Chapter 3.

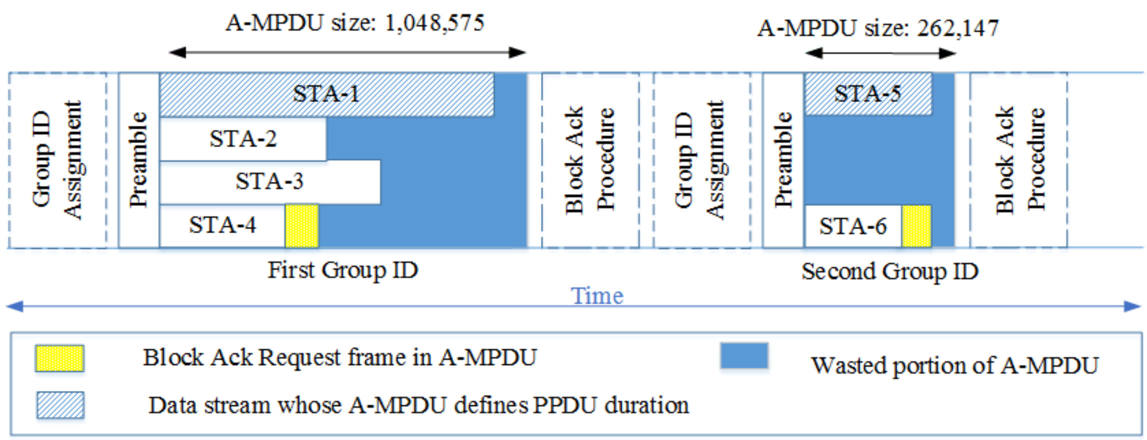
Concatenation of Long Data Streams in Consecutive Groups

To address this drawback [9], [10], concatenation of long data stream in consecutive groups is proposed. In this solution, average of selected A-MPDUs of all data streams is first calculated and then the A-MPDU size that fits the calculated average is selected. The long data streams that exceed the selected average A-MPDU are splitted to fit the average A-MPDU size. Within the A-MPDU, a Group ID assignment frame is appended to assign it the next Group ID for the remaining data MPDUs. Based on assumption, the MPDU fragmentation is possible and that data are transmitted with the same MCS index. As a result, calculation of PPDU duration is a function of A-MPDU size only. Block Acknowledgment process acknowledges the data streams that are terminated in the group. The next Group ID is assigned to new data streams with User Position IDs different from the one assigned to a long data steam. The size of the A-MPDU is the larger of either the average of all data streams A-MPDUs or the A-MPDU selected by previous group long data stream. The proposed method considerably reduces the transmission time.

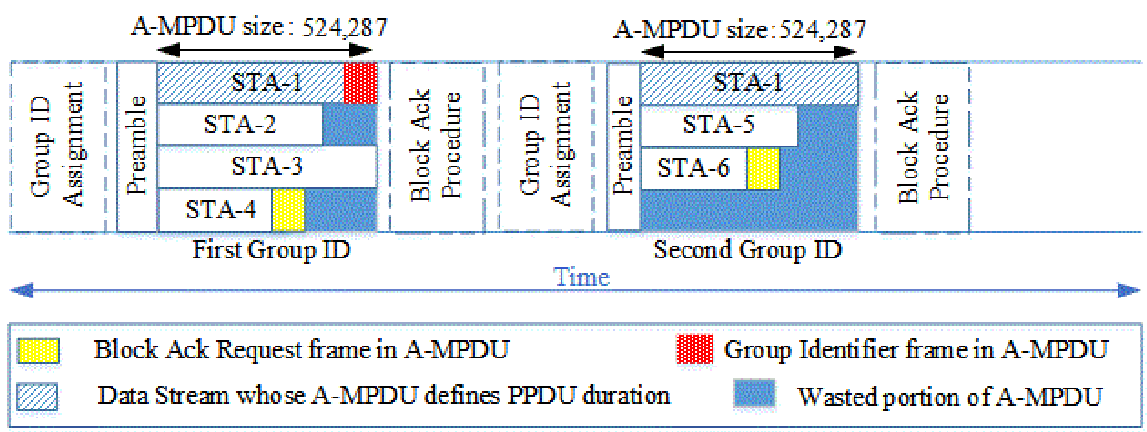
3.1. Example of VHT MU-MIMO Communication Process with and without Proposed Enhancement

Consider an AP wishes to communicate with 6 STAs via VHT MU-MIMO communication given in Figure 3-1(a). We assume that AP keeps tracks of all its STAs and that it has collected Steering Feedback from all STAs through the sounding process. We assume that all STAs communicate using the same MCS index. AP assigns first

Group ID to STA-1, STA-2, STA-3, and STA-4. It selects an A-MPDU of 1,048,575 octets to determine PPDU duration and then transmits respective A-MPDUs. After block acknowledgment procedure, second Group ID is assigned to STA-5 and STA-6 and their A-MPDUs are transmitted. The PPDU duration is based on the A-MPDU of 262,147 octets.



(a)



(b)

Figure 3-1. VHT MU-MIMO communication process: (a) Transmission of 6 data streams via VHT MU-MIMO communication process. (b) Transmission of 6 data streams via VHT MU-MIMO communication process with the proposed enhancement.

We now calculate transmission of STAs data using the procedure of concatenating long data streams into groups. As illustrated in Figure 3-1(b), the A-MPDU of the first group of four STAs is 524,287 octets. Since data of STA-1 exceed this size, a Group ID management frame is sent to the STA-1 assigning the next group ID within the A-MPDU. We presume the usual Block Acknowledgement and Group ID assignment process. Data from STA-1, STA-5, and STA-6 are transmitted with the A-MPDU size of 524,287 octets in the next transmitted group. The portion of wasted PPDU duration is now reduced.

3.2. Proposed Solution for the A-MPDU Size Selection Process

Taking average of A-MPDUs in a group provides significant improvement to VHT MU-MIMO throughput. In two cases, the average of A-MPDUs is not selected as A-MPDU size for the group. 1) If a data stream, whose part was transmitted in the previous group, should complete its transmission in the next subsequent group. Hence, the A-MPDU size of the group may be the largest A-MPDU size of the data stream belonging to the previous group. The reason is that the entire data stream should be acknowledged using one BA frame and its acknowledgement should not be delayed by splitting its transmission in multiple groups. 2) If at least two data streams select similar A-MPDU size, that A-MPDU size is selected as the A-MPDU size for the group. It offers two benefits: It ensures completion of at least two data streams and significant portion of other two streams. It also avoids a situation when selection of A-MPDU as an average leads to benefit of only few data streams while wasting octets of other data streams. For example, consider a case when the A-MPDU sizes of data streams are: 8,191, 524,287, 524,287, and 1,048,575. The selected A-MPDU size for the group is the average A-MPDU (1,048,575) shown in Table 1. With this choice, two data streams are empty halfway and the third only covers 1/128 of the allocated PPDU. However, if the A-MPDU size of 524,287 is selected, three data streams consume there complete PPDU durations and the wasted portion of the data stream with 8,191 octets is reduced by half. The selection of the A-MPDU size is shown in Figure 3-2.

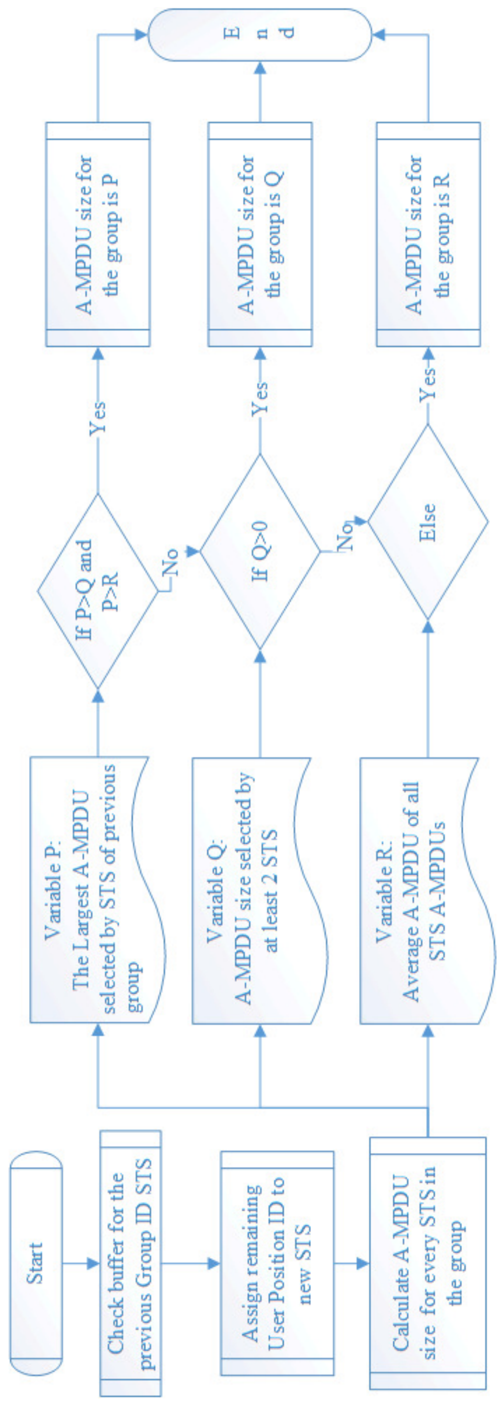


Figure 3-2. Proposed A-MPDU size selection process.

Chapter 4.

Simulation Results

We consider two types of simulations in order to evaluate the proposed enhancement. We first observe the improvement in transmission time with increase of data streams available for VHT MMU-MIMO communication. For a specified number of data streams, we also observe the difference in number of wasted A-MPDUs, transmission time, and control/management frames.

We generate a number of data streams ranging between 2,000 octets and 1,048,575 octets. For these data streams, various A-MPDU sizes may be selected from Table 1. We assume that all STAs agree on the same MCS index for transmission. Hence, only the A-MPDU size affects the PPDU duration. With the given data streams, we first calculate transmission time of the data streams by using the current VHT MU-MIMO communication process. The data stream with the largest A-MPDU size defines the PPDU duration of a group. Then, for the same data streams, we calculate transmission process using the proposed solution and selection of the A-MPDU size following the flow chart given in Figure 3-2.

In order to evaluate the difference in TX-time of both transmission processes, following assumptions are taken into consideration: 1. All STAs agree on transmission throughput of 26 Mbps, which is equivalent to the VHT MCS index 3 of a single space-time stream with modulation of 16 QAM of rate ½; 2. All STAs are receiving data with long Guard interval; 3. Only Block Convolution Coding (BCC) is used; 4. AP VHT Sounding process keeps track of all STAs positions over time; 5. Delayed Block Acknowledgment is accepted for communication; 6. MPDU frames inside the A-MPDU may be fragmented. Based on these assumptions, we calculate transmission time as:

$$TXTIME = T_{LSIG\_PR} + T_{L-SIG} + T_{VHT-SIG-A} + T_{VHT-PR} + T_{VHT-SIGB} + T_{SYML} \times N_{SYM}. \quad (1)$$

The preambles value is:

$$T_{LSIG\_PR} + T_{L-SIG} + T_{VHT-SIG-A} + T_{VHT-PR} + T_{VHT-SIGB} = 40\mu s. \quad (2)$$

The N_{SYM} of the data A-MPDU is:

$$N_{SYM} = m_{STBC} \times \lceil (8 \times APEP\_LENGTH + N_{service} + N_{tail} \times N_{ES}) / (m_{STBC} \times N_{DBPS}) \rceil. \quad (3)$$

where T_{SYML} = 4, m_{STBC} = 1, $N_{service}$ = 16, N_{tail} = 8, N_{ES}=1, N_{DBPS}= 104, and *APEP_LENGTH* = A-MPDU size as selected from Table 2-1 for STAs within a group. The list of variables is given in Table 4-1.

S/No.	Variable	Description
1	TLSIG_PR	Legacy Preamble
2	TL-SIG	Legacy Signaling Field
3	TVHT-SIG-A	Very High Throughput Signaling Field A
4	TVHT-PR	Very High Throughput Preamble
5	TVHT-SIG-B	Very High Throughput Signaling Field B
6	TSYML	Symbol Time
7	NSYML	Number of Symbols
8	mSTBC	Space Time Base Coding
9	Nservice	Number of service bits required for Block Convolutional Coding
10	Ntail	Number of tail bits for Block Convolutional Coding
11	NES	Number of Extra Symbols to se
12	NDBPS	Number of Data Bits Per Symbols for MCS symbol

Table 4-1 Description of variables used in calculating PPDU duration.

In addition to data transmissions there are also block acknowledgment and Group ID assignment intervals necessary for the VHT communication process, as shown in Figure 3-1(a) and Figure 3-1(b). The interval comprises of transmission of multiple management and control frames. These frames increase with the increased number of data streams. After every control/management frame and data stream, there is a transmission pause called Short Inter Frame Spacing. The duration of frames is calculated at transmission throughput of 26 Mbps, which is equivalent to the VHT MCS index 3. Duration of frames is shown in Table 4-2.

Transmission time of data streams is calculated using above equations. The time for transmitting control/management frames and SIFS are added.

Description	**Duration (µs)**	**Comment**
Block Acknowledgement (BA)	54	Transmission time includes preamble
Block Acknowledgement Request (BAR)	54	Transmission time includes preamble
Group ID assignment frame	60	Transmission time includes preamble
Short Interframe Spacing (SIFS)	16	Transmission free interval

Table 4-2. Duration of control frames, management frames, and Interframe Spacing.

Simulation results for increasing number of random generated data streams are shown in Figure 4-1. For the results shown in Figure 4-2, 4-3 and 4-4, 100 data streams were used and simulation was executed 10 times. In Figure 4-2, at every iteration, we observe a reduction of at least 1/2 s in transmission of 100 data streams with proposed enhancement when compared to standard VHT MU-MIMO process. Figure 4-3 shows the number of octets that are prevented from being wasted with the proposed enhancement.

In simulations of 100 data streams, 4 data streams are assigned a group by the current 802.11ac standard thus utilizing 25 Group IDs. In the proposed approach, the requirement of Group IDs increases to 27-30 because some data streams are part of two groups. The increase of Group IDs may increase the number of Group ID management frames. However, the number of frames is comparable to the standard VHT MU-MIMO process because every long data stream is assigned the next Group ID within an A-

MPDU. Furthermore, the number of Block Acknowledgement (BA) and Block Acknowledgement Request (BAR) frames is slightly smaller because additional groups provide an opportunity to transmit additional BAR frames in the A-MPDUs. Adding BA/BAR frames and Group ID assignment frames, we observe that the proposed approach does not require additional control/management frames. Hence, there is no additional overhead in time and no extra TXOP needs to be allocated to control/management frames. These results are verified through simulations and are shown in Figure 4-4.

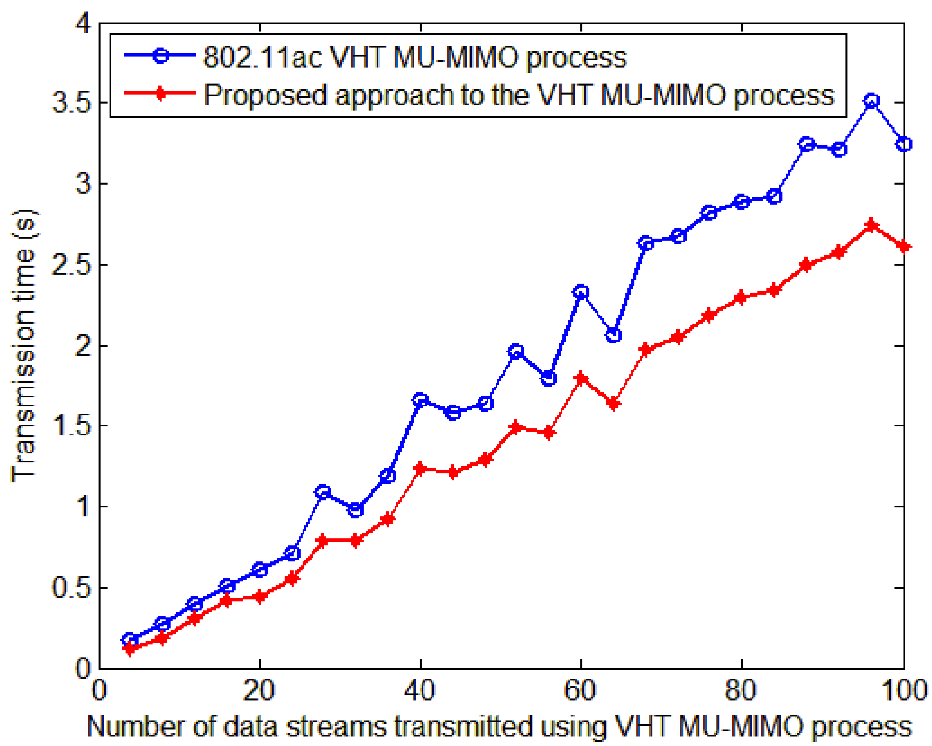


Figure 4-1. Comparison of the proposed approach and the VHT MU-MIMO process.

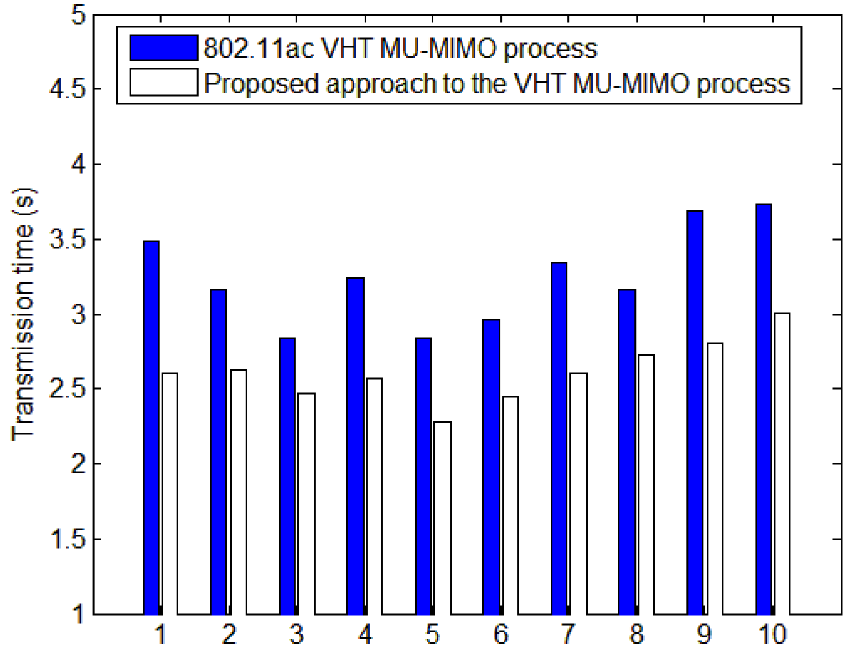


Figure 4-2. Performance comparison of 10 simulations: Transmission time.

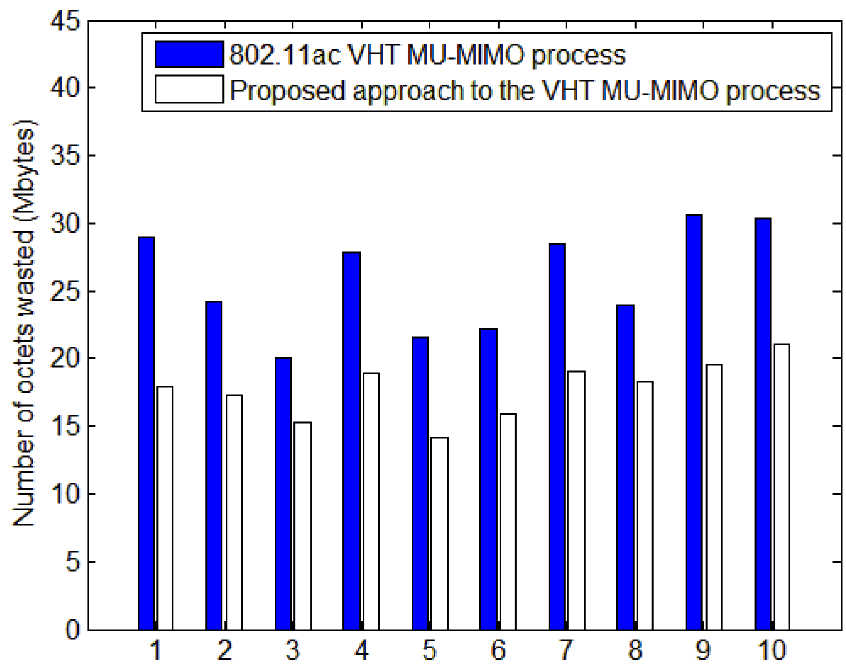


Figure 4-3. Performance comparison of 10 simulations: Number of wasted octets.

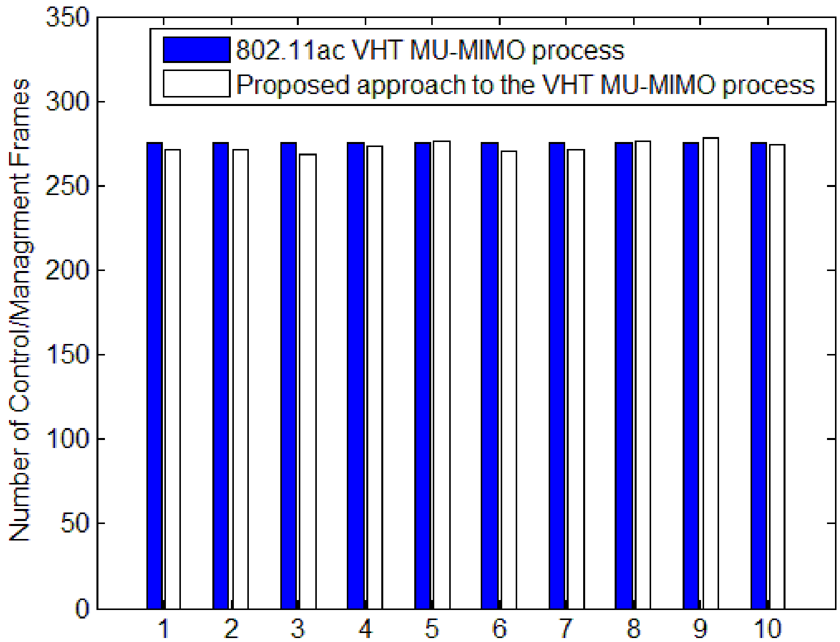


Figure 4-4. Performance comparison of 10 simulations: Control /Management frames.

Chapter 5.

Conclusion

Wireless LANs are one of the most influential technologies of 21st century. This technology allows wireless communication of locally available devices over the unlicensed free spectrum. The unlicensed spectrum is shared with other technologies and there is power restriction by regulatory authorities. Hence, it is a challenging task to achieve a better communication model for WLANs that competes for throughput with wired LANs. IEEE introduced task groups for 802.11 standards. These task groups are responsible to setting MAC and PHY Layer specifications for successful communication of devices over half-duplex wireless channels. In 2013, the 802.11ac task group published an updated draft of the 802.11ac standard. The draft has many upgrades and additional technologies over its predecessors 802.11/ab/g/n. On the MAC Layer, the standard specifies frame aggregation for increased number of data frames in form of Aggregated Multi-Protocol Data Unit (A-MPDU). These aggregated frames are acknowledged by single Block Acknowledgment (BA) frame under Reverse Direction Protocol (RDP). On the PHY Layer, beamforming is now part of the standard in form of Null Data Packet (NDP) sounding protocol. Through beamforming, an AP keeps track of STAs and ensures that the data carrying signals are received by specific STA and are nullified in direction of other STAs. Group ID assignment process and VHT preambles are introduced in 802.11ac for Very High Throughput (VHT) Multi-User Multiple Input Multiple Output (VHT MU-MIMO) process.

VHT MU-MIMO is an efficient communication mode that allows an Access Point to communicate with maximum 4 stations simultaneously over the same channel. In this mode, 802.11ac allows an AP to take advantage of space diversity to perform beamforming process using NDP sounding protocol. The recipient STAs are assigned

Group ID and Position ID via Group ID assignment frame. Under the beamformed signals, numerous signals are transmitted to specified STAs. VHT preambles provide the specifications to the STAs for extraction of data from data streams.

The VHT MU-MIMO communication process inherits a drawback of wasting part of PPDU of short data stream when data streams of un-equal duration are grouped in a Group ID. To reduce this waste, we propose a solution of concatenation long data streams into consecutive groups by sending either the average of all data streams A-MPDUs or the A-MPDU that was selected by the previous group long data stream. The proposed enhancement is compared with the current VHT MU-MIMO communication process. Significant improvements are observed such as reduction of wasted octets, reduction in transmission time, and increase in throughput.

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Appendix A.

Simulation Code

The VHT MU-MIMO communication process is simulated in MATLAB. The MATLAB code consists of six functions: Main Function, Data Generator, Assign A-MPDU Default, Assign A-MPDU Proposed, Current VHT-MU-MIMO, and Upgraded VHT-MU-MIMO.

A.1 Main Function

This is the interface function that executes all the other functions and generates graphs and figures.

```
function Main

for x=1:25

for i=1:10

[Data_frames]=Data_Generator(x*4); % Function to generate input data
[Octet(i), GID(i), EoF(i), BA(i), BAR(i), GID_frames(i),Octeti,  TX_time_data(i), TX_time_of_BAs(i),
TX_time_of_BARs(i), TX_time_GID_frames(i), Total_SIFS_time(i),Total_total(i)] =
Current_VHTMIMO(Data_frames); % Function which provides the parameters from current VHT-MU-
MIMO process including total time consumed in microseconds
[GOctet(i), GGID(i), GEoF(i), GBA(i), GBAR(i), GGID_assignment(i), GOctet,   GTX_time_data(i),
GTX_time_of_BAs(i), GTX_time_of_BARs(i), GTX_time_GID_frames(i),
GTotal_SIFS_time(i),GTotal_total(i) ] = GID_alt_VHTMIMO(Data_frames); % Function which provides
the parameters from proposed VHT-MU-MIMO process including total time consumed in microseconds
end
W(x,1)=mean(Total_total);
Q(x,1)=mean(GTotal_total);

end
Total_total=Total_total/1000000;
GTotal_total=GTotal_total/1000000;
G=[Total_total ;GTotal_total];
G=transpose(G);
e=[1:10];
figure(1)
%bar(x,[Total_total GTotal_total] );
h=bar(e,G);
 legend('802.11ac VHT MU-MIMO process','Proposed approach to the VHT MU-MIMO process');
set(h(1),'facecolor','b')
set(h(2),'facecolor','w')
 set(gca,'FontSize',12)
```

```
 ylabel('TXtime (seconds)');
axis([0 11 1 5]);
%hold off

EoF=EoF/1000000;
GEoF=GEoF/1000000;
F=[EoF;GEoF];
figure(2)
F=transpose(F);
h=bar(e,F);
set(h(1),'facecolor','b')
set(h(2),'facecolor','w')
legend('802.11ac VHT MU-MIMO process','Proposed approach to the VHT MU-MIMO process');
%xlabel('Number of Iterations of the simulation');
axis([0 11 0 45]);
set(gca,'FontSize',12)
ylabel('Number of Octets wasted (Mega bytes)');

H=[BA+BAR;GBA+GBAR];
H=transpose(H);
figure(3)
h=bar(e,H);
set(h(1),'facecolor','b')
set(h(2),'facecolor','w')
axis([0 11 0 220]);
set(gca,'FontSize',12)
%xlabel('Number of Iterations of the simulation');
ylabel('Number of BA & BAR frames');
%legend('802.11ac VHT MU-MIMO communication','Proposed upgradation to standard','northwest');
legend('802.11ac VHT MU-MIMO process','Proposed approach to the VHT MU-MIMO process');

I=[ GID_frames;GGID_assignment];
I=transpose(I);
figure (4)
set(gca,'FontSize',12)
h=bar(e,I);
set(h(1),'facecolor','b')
set(h(2),'facecolor','w')
axis([0 11 1 130]);
%xlabel('Number of Iterations of the simulation');
%axis([0 11 1 150]);
ylabel('Number of Group-ID assignment frames');
legend('802.11ac VHT MU-MIMO process','Proposed approach to the VHT MU-MIMO process');

%Resultant= Total_total-GTotal_total; %Differnce in time consumed by both VHT MU-MIMO processes.
The proposed solution saves at least 2 sec for the 100 frames in this simulation
%plot(Octeti)

figure(5)
plot([4:4:100],W/1000000,'b-o');
hold on
plot([4:4:100],Q/1000000,'r-*');
axis([0 100 0 4]);
```

```
set(gca,'FontSize',12)
xlabel('Number of data streams transmitted using VHT MU-MIMO process');
ylabel('Tx Time in seconds');
legend('802.11ac VHT MU-MIMO process','Proposed approach to the VHT MU-MIMO process');
hold off

%plot(Octeti/100000, [1:GID])
end
```

A.2 Data Generator

This function randomly generate desired amount of data stream in octets. Range of data streams is set between 2,000 and 1,048,575 octets to fit A-MPDU sizes of 802.11ac.

```
function [R_data, Input_data] = Data_Generator(S)
%Generate Random input Data representing S input A-MPDU frames of Stations such that it requires A-
MPDU sizes of 8192, 16384, 32767, 65535, 131071, 262153, 524287, 1048575
%S=40;
Input_data=randi(8,1,S);
V=0;D=0;
for i=1:S
   if(Input_data(1,i)==1)
      V=V+1;
   else
      D=D+1;
   end

end
Vvalues=randi(1000000,1,V);
Dvalues=randi(250000,1,D);
for i=1:D
   if(Dvalues(i)<10)
      Dvalues(i)=Dvalues(i)*1000;
   end
   if (Dvalues(i)<100)
     Dvalues(i)=Dvalues(i)*100;
   end
   if (Dvalues(i)<1200)
      Dvalues(i)=Dvalues(i)*15;
   end
end
%Priority number of frames for future use
for i=1:V
   if(Vvalues(i)<10)
      Vvalues(i)=Vvalues(i)*1000;
   end
   if (Vvalues(i)<100)
     Vvalues(i)=Vvalues(i)*100;
      end
   if (Vvalues(i)<1200)
```

```
        Vvalues(i)=Vvalues(i)*15;
    end
end

X=Dvalues;
R_data=zeros(1,S);
x=1;
y=1;

for i=1:S
    if(Input_data(1,i)==1)

        R_data(1,i)=Vvalues(x);
        x=x+1;
    else
        R_data(1,i)=Dvalues(y);
        y=y+1;
    end
end

end
```

A.3 Assign A-MPDU: Default

This function takes any number of data streams. It finds their respective A-MPDU size and selects the largest A-MPDU size.

```
function [MPDU_size] = Assign_MPDU_default(Input)
[p,qty]=size(Input);
MPDU_size=zeros(1,qty);
        for i=1:qty

                if(Input(i)<8191)
                 MPDU_size(i)=8191;
                end
                if(8192<=Input(i) && Input(i)<16383)
                 MPDU_size(i)=16383;
                end
                if(16384<=Input(i) && Input(i)<32767)
                 MPDU_size(i)=32767;
                end
                if(32768<=Input(i) && Input(i)<65535)
                 MPDU_size(i)=65535;
                end
                if(65536<=Input(i) && Input(i)<131071)
                 MPDU_size(i)=131071;
                end
                if(131072<=Input(i) && Input(i)<262143)
                 MPDU_size(i)=262143;
                end
                if(262144<=Input(i) && Input(i)<524287)
```

```
                    MPDU_size(i)=524287;
                    end

                    if(524288<=Input(i) && Input(i)<=1048575)
                    MPDU_size(i)=1048575;
                    end

          end
end
```

A.4 Assign A-MPDU: Proposed

This function uses the flow chart shown in Fig. 3-2

to specify A-MPDU size for the group.

```
function [Y] = Assign_MPDU(Input)
[p,S]=size(Input);
MPDU_size=zeros(1,S);
MPDU_size=Assign_MPDU_default(Input);

   X=(MPDU_size(1)+MPDU_size(2)+MPDU_size(3)+MPDU_size(4))/4;
    if(MPDU_size(1)==MPDU_size(2))
   Y=MPDU_size(1);
   end
    if(MPDU_size(1)==MPDU_size(3))
  Y=MPDU_size(1);
    end
    if (MPDU_size(1)==MPDU_size(4))
   Y=MPDU_size(1);
    end
    if (MPDU_size(2)==MPDU_size(3))
   Y=MPDU_size(2);
    end
     if (MPDU_size(2)==MPDU_size(4))
  Y=MPDU_size(2);
     end
    if (MPDU_size(3)==MPDU_size(4))
   Y=MPDU_size(3);
    end

      if(X<8191)
   Y=8191;
      end
      if(8192<=X && X<16383)
   Y=16383;
      end
      if(16384<=X && X<32767)
  Y=32767;
      end
      if(32768<=X && X<65535)
```

```
 Y=65535;
    end
    if(65536<=X && X<131071)
 Y=131071;
    end
    if(131072<=X && X<262143)
 Y=262143;
    end
    if(262144<=X && X<524287)
 Y=524287;
    end
    if(524288<=X && X<=1048575)
 Y=1048575;
    end

  end
```

A.5 Current VHT-MU-MIMO

This function simulates standard VHT MU-MIMO process and uses default A-MPDU assignment process to return parameters such as octets wasted, transmission time, and number of control/management frames.

```
function [Octet, GID, EoF, BA, BAR, GID_frames,N_Octets, TX_time_data, TX_time_of_BAs,
TX_time_of_BARs, TX_time_GID_frames, Total_SIFS_time,Total_total] = Current_VHTMIMO(D_data)
[p,sze]=size(D_data);
%This code strictly follows the MU-MIMO communication precedure givn in 802.11ac standard draft.
GID_frames=0;
a=sze/4;
%Checkpoint=zeros(a,1);
GID=0;   %Group identifier
Octet=0;  %Size of A-MPDU selected
BAR=0;  % Block acknowledgement request as separate frame
BA=0;   % Block acknowledgement as separate frame
X=zeros(4,1);
EoF_padding=zeros(sze/4,1);  % Portion of A-MPDU wasted also pointed out by Hu-Jin [3]
mSTBC=1;
Nser=16;
Nes=1;
Ntail=6;
Nsym=zeros(a,1);
NDBPS=104;   %change it if MCS is changed
F=0;
e=0;
N_Octets=zeros(sze/4,1);
MPDUsize=Assign_MPDU_default(D_data);
Norma=zeros(sze/4,1);
mEAn=zeros(sze/4,1);
% Assign MPDU for the one with maximum data
for i=1:4:sze
  e=e+1;
```

```
 GID=GID+1;
 X=[MPDUsize(i) MPDUsize(i+1) MPDUsize(i+2) MPDUsize(i+3)];

 EoF_padding(i,1)=max(X)-D_data(i);
 EoF_padding(i+1,1)=max(X)-D_data(i+1);
 EoF_padding(i+2,1)=max(X)-D_data(i+2);
 EoF_padding(i+3,1)=max(X)-D_data(i+3);

F=F+1;
Nsym(F,1)= mSTBC * (8*max(X)+Nser+Ntail*Nes)/(mSTBC * NDBPS);
%Checkpoint(F,1)=Nsym(F,1);
Octet=Octet+max(X);
Norma(e,1)=norm(X);
mEAn(e,1)=mean(X);
BAR=BAR+3; % One BAR might be sent within the A-MPDU
BA=BA+4;
GID_frames=GID_frames+4;
N_Octets=Norma;
end

EoF=sum(EoF_padding);  % Portion of A-MPDU wasted also pointed out by Hu-Jin [3]

%Calculate time in Microseconds

TX_time_data=sum(40+4*Nsym);
TX_time_of_BAs=BA*(4+40);            %6*44
TX_time_of_BARs=BAR*(4+40);           %5*44
TX_time_GID_frames=GID_frames*(8+40); %6x48
Total_SIFS_time=sum(BA+BAR+GID_frames+GID)*16;
Total_total=TX_time_data+TX_time_of_BAs+TX_time_of_BARs+TX_time_GID_frames+Total_SIFS_ti
me;

%imems_of_data_octet=((Octet/1232)*180)+42*GID+16*GID;    % for 20MHz, 1 stream, 64-QAM, BCC
encoder of rate 5/6, A 1232 Octet takes 180 microsec + 42 microsec preamble per group-ID +16 microsec
SIFS per group-ID.
%ms_BA=BA*(4+40+16);
% Block Ack= 8 size of frame+ 42 size of preamble + 16 size of SIFS
%ms_BAR=BAR*(4+40+16);
% Block Ack Request= 8 ms size of frame+ 42 ms size of preamble + 16 ms size of SIFS
%ms_GID_frames=GID_frames*(8+40+16);
% Assign Group identifier frames= 8 ms size of frame+ 42 ms size of preamble + 16 ms size of SIFS
%Sum=ms_of_data_octet+ms_BA+ms_BAR+ms_GID_frames;
% Calculating total time.

End
```

A.6 VHT-MU-MIMO Communication with the Proposed Enhancement

This function implements VHT MU-MIMO process with proposed enhancement and returns parameters such as octet wasted, transmission time, and number of control/management frames.

```
function [Octet, GID, EoF_padding, BA, BAR, GID_assignment,N_OCtets, TX_time_data,
TX_time_of_BAs, TX_time_of_BARs, TX_time_GID_assignment, Total_SIFS_time,Total_total ] =
GID_alt_VHTMIMO(Input)
[p,sze]=size(Input);
%This code provides proposed MU-MIMO communication procedure in which
%incomplete data A-MPDU is assigned alternate G-ID
N_Octets=zeros(200,1);
Norma=zeros(200,1);
mEAn=zeros(200,1);
Checkpoint=zeros(200,1);
GID=0;     % Number of Group-IDs
Octet=0;   % Total size of data A-MPDU
mSTBC=1;
Nser=16;
Nes=1;
MPDU_nested=0;
Ntail=6;
Nsym=zeros(100,1);
NDBPS=104;  %change it if MCS is changed
F=0;
EoF_padding=0;  % Portion of A-MPDU wasted
BA=0;      %   Number of BA frames
BAR=0;     % Number of BAR frames
X=zeros(4,1);
i=1;
m=4;
s=0;
l=0;
buf=zeros(4,1);
GID_assignment=0;   % Number of Group-ID assignment frames.

while i<sze
  if(i+1>=sze-1)
       buf(2)=Input(sze);
       buf(3)=Input(sze-1);
      break
  end
X=0;
MPDU_nested=0;
GID=GID+1;
 s=s+1;
 if m==0
    X=[buf(1) buf(2) buf(3) buf(4)];
    l=l-4;
   MPDU_nested=max(Assign_MPDU_default(X));
```

```
end
if m==1
   X=[buf(1) buf(2) buf(3) Input(i)];
   l=l-3;
   MPDU_nested=max(Assign_MPDU_default([buf(1) buf(2) buf(3)]));
 %   MPDU_size=Assign_MPDU_default(buf(1));
end
if m==2
   X=[buf(1) buf(2) Input(i) Input(i+1)];
   l=l-2;
  MPDU_nested=max(Assign_MPDU_default([buf(1) buf(2)]));
end
 if m==3
   X=[buf(1) Input(i) Input(i+1) Input(i+2)];
   l=l-1;
  MPDU_nested=max(Assign_MPDU_default(buf(1)));
end
if m==4
   X=[Input(i) Input(i+1) Input(i+2) Input(i+3)];
 %   MPDU_size=Assign_MPDU(X);
end

i=i+m;
buf(1)=0;  buf(2)=0;  buf(3)=0;  buf(4)=0;
MPDU_size=Assign_MPDU(X);

if MPDU_nested> MPDU_size
    MPDU_size=MPDU_nested;
end

Norma(s,1)=norm(X);
% mEAn(s,1)=mean(X);
Y = [X(1)-MPDU_size X(2)-MPDU_size X(3)-MPDU_size X(4)-MPDU_size ];

if Y(1)>100
   buf(1)=Y(1)+52;
   l=l+1;
   BAR=BAR-1;
   BA=BA-1;
else
   EoF_padding=EoF_padding+Y(1);     % Portion of A-MPDU wasted also pointed out by Hu-Jin [3]
   %BAR=BAR-1;
end

if Y(2)>100
   buf(2)=Y(2)+52;
   l=l+1;
   BAR=BAR-1;
   BA=BA-1;
else
   EoF_padding=EoF_padding+Y(2) ;    % Portion of A-MPDU wasted also pointed out by Hu-Jin [3]
   %BAR=BAR-1;
end
```

```
 if Y(3)>100
    buf(3)=Y(3)+52;
    l=l+1;
    BAR=BAR-1;
    BA=BA-1;
 else
    EoF_padding=EoF_padding+Y(3)  ;   % Portion of A-MPDU wasted also pointed out by Hu-Jin [3]
    %BAR=BAR-1;
 end
 if Y(4)>100
    buf(4)=Y(4)+52;
    l=l+1;
    BAR=BAR-1;
    BA=BA-1;
 else
    EoF_padding=EoF_padding+Y(4) ;    % Portion of A-MPDU wasted also pointed out by Hu-Jin [3]
    %BAR=BAR-1;
 end
 F=F+1;
Nsym(F,1)= mSTBC * (8*MPDU_size+Nser+Ntail*Nes)/(mSTBC * NDBPS);
Checkpoint(F,1)=Nsym(F,1);
 buf=sort(buf,'descend');
 Octet=Octet+MPDU_size;
 m=4-l;

 GID_assignment=GID_assignment+m;
 BAR=BAR+4;
 BA=BA+4;

end


if buf(1)>0
   GID=GID+1;
  % M= [buf(1) buf(2) buf(3)];
 MPDU_size=Assign_MPDU_default(buf(1));
 Octet=Octet+MPDU_size;
 BAR=BAR+1;
 BA=BA+1;
 Norma(GID,1)=norm(buf(1), Input(sze));
 %mEAn(GID,1)=mean(buf(1), Input(99), Input(100));
end
BAR=BAR-GID;
EoF_padding=-1*EoF_padding;
N_OCtets=zeros(GID,1);
CHECKPOINT=zeros(GID,1);
for u=1:GID
   N_OCtets(u,1)=Norma(u,1);
   CHECKPOINT(u,1)=Checkpoint(u,1);
end
%Calculate time in Microseconds

GID_assignment=GID_assignment+3;
BA=BA+3;
```

```
TX_time_data=sum(40+4*Nsym);
TX_time_of_BAs=BA*(16+40);
TX_time_of_BARs=BAR*(16+40);
TX_time_GID_assignment=(GID_assignment)*(20+40);
Total_SIFS_time=sum(BA+BAR+GID_assignment+GID)*16;
Total_total=TX_time_data+TX_time_of_BAs+TX_time_of_BARs+TX_time_GID_assignment+Total_SIFS_time;
%imems_of_data_octet=((Octet/1232)*180)+42*GID+16*GID;    % for 20MHz, 1 stream, 64-QAM, BCC encoder of rate 5/6, A 1232 Octet takes 180 microsec + 42 microsec preamble per group-ID +16 microsec SIFS per group-ID.
%ms_BA=BA*(4+40+16);                       % Block Ack= 8 size of frame+ 42 size of preamble + 16 size of SIFS
%ms_BAR=BAR*(4+40+16);                     % Block Ack Request= 8 ms size of frame+ 42 ms size of preamble + 16 ms size of SIFS
%ms_GID_frames=GID_frames*(8+40+16);       % Assign Group identifier frames= 8 ms size of frame+ 42 ms size of preamble + 16 ms size of SIFS

%Sum=ms_of_data_octet+ms_BA+ms_BAR+ms_GID_frames;          % Calculating total time.

End
```