Analysis Of WLAN IEEE Standard 802.11N Over Legacy Wi-Fi Standards

Major Project Thesis

Submitted in fulfillment of the requirements
for the degree of

Master of Technology
in
Electronics & Communication Engineering
(Embedded Systems)

Submitted By
Hardik Dabhi
(22MECE01)

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING
INSTITUTE OF TECHNOLOGY
NIRMA UNIVERSITY
AHMEDABAD-382481
Dec 2023

Analysis Of WLAN IEEE Standard 802.11N Over Legacy Wi-Fi Standards

Major Project

Submitted in
partial fulfillment of the requirements
for the degree of

Master of Technology in
Electronics & Communication Engineering
(Embedded Systems)

Submitted By

Hardik Dabhi
(22MECE01)

External Project Guide:	**Internal Project Guide:**
Mr. Divesh Dave	**Dr. Manish Patel**
Pre-Cert QA Manager	Asso. Professor, EC Department,
NXP India Pvt. Ltd.,	Institute of Technology,
Pune, Maharashtra.	Nirma University, Ahmedabad.

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING
INSTITUTE OF TECHNOLOGY
NIRMA UNIVERSITY
AHMEDABAD-382481
May 2023

NIRMA
UNIVERSITY
INSTITUTE OF TECHNOLOGY
NAAC ACCREDITED ‘A+’ GRADE

Certificate

This is to certify that the major project entitled **”Analysis Of WLAN IEEE Standard 802.11N Over Legacy Wi-Fi Standards Over 802.11G”** submitted by **Hardik Dabhi (Roll No: 22MECE01)**, towards the partial fulfillment of the requirements for the award of the degree of Master of Technology in Electronics & Communication Engineering (Embedded Systems) of Nirma University, Ahmedabad, is the record of work carried out by him under my supervision and guidance. In my opinion, the submitted work has reached the level required for being accepted for examination. The results embodied in this major project, to the best of my knowledge, haven’t been submitted to any other university or institution for the award of any degree or diploma.

Dr. Manish Patel
Internal Guide ,
Associate Professor,
EC Department,
Institute of Technology,
Nirma University, Ahmedabad.

Dr. Nagendra Gajjar
Coordinator M.Tech - EC(ES)
Professor,
EC Department,
Institute of Technology,
Nirma University, Ahmedabad

Dr. Usha Mehta
Professor and Head,
EC Department,
Institute of Technology,
Nirma University, Ahmedabad.

Dr. Rajesh Patel
Director,
Institute of Technology,
Nirma University, Ahmedabad

External Certificate

This is to certify that the major project entitled **“Analysis Of WLAN IEEE Standard 802.11N Over Legacy Wi-Fi Standards Over 802.11G”** submitted by **Hardik Dabhi (Roll No: 22MECE01)**, towards the partial fulfillment of the requirements for the award of the degree of Master of Technology in Electronics & Communication Engineering (Embedded Systems) of Nirma University, Ahmedabad, is the record of work carried out by him under my supervision and guidance. In my opinion, the submitted work has reached the level required for being accepted for examination.

Mr. Divesh Dave
Wi-fi Pre-cert QA Manager,
NXP India Pvt. Ltd.,
Pune, Maharashtra, India.

Statement of Originality

I, **Hardik Dabhi**, Roll. No. **22MECE01**, give undertaking that the Major Project entitled "**Analysis Of WLAN IEEE Standard 802.11N Over Legacy Wi-Fi Standards**" submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in **Electronics & Communication Engineering (Embedded Systems)** of Institute of Technology, Nirma University, Ahmedabad, contains no material that has been awarded for any degree or diploma in any university or school in any territory to the best of my knowledge. It is the original work carried out by me and I give assurance that no attempt of plagiarism has been made.It contains no material that is previously published or written, except where reference has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

Signature of Student
Date:
Place:

Endorsed by
Mr. Divesh Dave
(External Guide)

Dr. Manish Patel
(Internal Guide)

Acknowledgements

It gives me immense pleasure in expressing thanks and profound gratitude to **Divesh Dave, Ashok Arugnuman, Sanika Gadge, Gayatri Bhamare, Kritika Agarawal and NXP team**, Embedded Software Development Manager, NXP India Pvt. Ltd, Pune, Maharashtra for their valuable guidance and continual encouragement throughout this work. The appreciation and continual support they have imparted have been a great motivation to me in reaching a higher goal. Their guidance has triggered and nourished my intellectual maturity that I will benefit from, for a long time to come.

It gives me immense pleasure in expressing thanks and profound gratitude to **Dr. Manish Patel**, Associate Professor, Electronics & Communication Engineering Department, Institute of Technology, Nirma University, Ahmedabad for his valuable guidance and continual encouragement throughout this work. The appreciation and continual support he has imparted has been a great motivation to me in reaching a higher goal. His guidance has triggered and nourished my intellectual maturity that I will benefit from, for a long time to come.

It gives me an immense pleasure to thank **Dr. Nagendra Gajjar**, Coordinator M.Tech - EC(ES) of Electronics & Communication Engineering Department, Institute of Technology, Nirma University, Ahmedabad for his kind support and providing basic infrastructure and healthy research environment.

It gives me an immense pleasure to thank **Dr. Usha Mehta**, Hon'ble Head of Electronics & Communication Engineering Department, Institute of Technology, Nirma University, Ahmedabad for his kind support and providing basic infrastructure and healthy research environment.

A special thank you is expressed wholeheartedly to **Dr. Rajesh Patel**, Hon'ble Director, Institute of Technology, Nirma University, Ahmedabad for the unmentionable motivation he has extended throughout course of this work.

I would also thank the Institution, all faculty members of Electronics & Communication Engineering Department, Nirma University, Ahmedabad for their special attention and suggestions towards the project work.

- Hardik Dabhi
22MECE01

Abstract

This study offers a thorough analysis of the WLAN IEEE standard 802.11n, scrutinizing its performance in comparison to legacy Wi-Fi standards. The focus is on dissecting key technological advancements, notably Multiple Input Multiple Output (MIMO) technology, dual-band operation, and channel bonding. The research systematically evaluates how these features contribute to improved data rates, extended coverage range, and enhanced overall network efficiency when juxtaposed against legacy Wi-Fi standards. MIMO technology, with its ability to facilitate multiple data streams concurrently, is examined for its impact on throughput, addressing limitations present in earlier standards. The dual-band operation in 802.11n, operating in both 2.4GHz and 5GHz frequencies, is explored to understand its role in mitigating interference and optimizing performance, providing a marked departure from the limitations of legacy standards. Channel bonding, a distinctive feature of 802.11n, is analyzed for its capacity to enable wider channel widths, consequently elevating data rates beyond what was achievable in legacy Wi-Fi standards. The study also considers the implications of these technological advancements on the efficiency of the overall network, emphasizing improvements in areas such as reliability, speed, and adaptability to modern usage patterns. Through this detailed analysis, the research aims to offer comprehensive insights into the transformative aspects of 802.11n over legacy Wi-Fi standards. These insights are intended to inform decision-making processes related to network design, device compatibility, and the strategic integration of advanced and legacy technologies within wireless environments.

Abbreviations

OEM : Original Equipment Manufacturer
DFS : Dynamic Frequency Sequence
BSS : Basic Service Set
IBSS : Independent Basic Service Set
ESS : Extended Service Set
MAC : Medium Access Control
TX : Transmitter
RX : Receiver
ODM : Original Design Manufacturers
HT : High Throughput
VHT : Very High Throughput
HE : High Efficiency
EDCA : Enhanced Distributed Channel Access:
RIFS : Reduced Inter-Frame Space
MSDU : Mac Service Data Unit
MPDU : Mac Protocol Data Unit
PSDU : PLCP Service Data Unit
FCS : Frame Check Sequence
DS : Distributed System
PCO : Phased Coexistence Operation
SDIO : Serial Digital Input Output
PCIE : Peripheral Component Interconnect Express
HTC : High Throughput Capabilities
FTR : Fast Transition Roaming
TKIP : Temporal Key Integrity Protocol
WEP : Wired Equivalent Protocol
WPA : Wi-Fi Protected Access
AES : Advanced Encryption Standard
RC4 : Rivest Cipher 4
MIMO : Multi Input Multi Output
MUMIMO : Multi User Multi Input Multi Output
OFDMA : Orthogonal Frequency Division Multiplexing
DHCP : Dynamic Host Configuration Protocol
SMTP : Simple Mail Transfer Protocol
ICMP : Internet Control Message Protocol
TCP : Transmission Control Protocol
UDP : User Datagram Protocol
ISP : Internet Service Provider
QoS : Quality Of Service
MCS : Modulation And Coding Scheme
SS : Spatial Stream

BPSK : Binary Phase Shift Keying
DPSK : Differential Phase Shift Keying
QPSK : Quadrature Phase Shift Keying
PSK : Phase Shift Keying
QAM : Quadrature Amplitude Modulation :
MFSK : Minimum Frequency Shift Keying
SNR : Signal To Noise Ratio
RSSI : Received Signal Strength Indicator
db : Decibel
LMSC : Lan/Man Standard Committee
FPGA : Field Programmable Gate Array
SSID : Service Set Identifier
ISM : Industrial, Scientific And Medical Use
EAP : Extensible Authentication Protocol
WPS : Wi-Fi Protected Setup
CRC : Cyclic Redundancy Check
RSNA : Robust Security Network
IV : Initialization Vector
ICV : Integrity Check Value
WFA : Wi-Fi Alliance
MIC : Message Integrity Code
EAPOL : Extensible Authentication Protocol Over Lan
AAA : Authentication, Authorization And Accounting
MRC : Maximum Ratio Combining
DLS : Direct Link Setup
PMF : Protected Management Frames
PSK : Pre-Shared Keys
SBK : Server Based Keys
AKM : Authentication Key Management
PBKDF : Password Based Key Derivation Function
PMK : Pairwise Master Key
PTK : Pairwise Temporal Key
RADIUS : Remote Authentication Dial:In User Service
DNS : Domain Name Server
PLCP : Physical Layer Convergence Protocol
PMD : Physical Medium Dependent
EDCA : Enhanced Distributed Channel Access
HCCA : Hybrid Co-Ordinated Channel Access
ERP : Ethernet Ring Protection Switching
MLME : Mac Sublayer Management Entity
TIM : Traffic Indication Map
IFS : Inter Frame Spaces
RIFS : Reduced Inter-Frame Space
SIFS : Short Inter-Frame Space
PIFS : PCF Inter-Frame Space
DIFS : DCF Inter-Frame Space
AIFS : Arbitrary Inter-Frame Space
EIFS : Extended Inter-Frame Space
IPC : Inter Process Communication

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Prologue

The Internet of Things (IoT) enables the system to become entirely automated. Interoperability between the many networked devices requires the use of a variety of communication protocols. The term “wireless communication protocol” refers to a standard operating procedure that specifies how a variety of electronic devices may communicate with one another while using wireless media[2]. When talking about wireless technology, the four primary networking protocols that are discussed are Wi-Fi, Bluetooth, ZigBee, and cellular. It is essential to bear in mind that each one of them was first built to fulfill the needs of a different set of applications[3].

Because Wi-Fi was developed to replace the Ethernet wire, fast data speed was valued over simplicity and power efficiency. The serial wire was replaced with Bluetooth, which also has a quality-of-service overhead for voice communication[4]. substantially less power-intensive than Wi-Fi. Bluetooth can only support a small network of seven slave devices and has a significant pairing delay. It is a technique that is preferred over several IoT network protocols for wirelessly transferring data over short distances.

It makes use of ISM band short-wavelength UHF radio waves with a frequency range of 2.4 to 2.485 GHz. Based on the applications, there are three different versions of Bluetooth technology: Bluetooth, BLE (Bluetooth 4.0 or Bluetooth Low Energy), and iBeacon[5]. ZigBee was made to make large, reliable sensor networks with cheap, low-power nodes. Its maximum range is between 10 and 100 meters, and the data rate used to send information between devices is about 250 Kbps, which is much less than the throughput of Wi-Fi or Bluetooth[6]. ZigBee is widely used in sense-and-control applications like home/building automation, advanced metering, and health/fitness monitoring. It was the first protocol designed to work on the IEEE Std 802.15.4 radio.

It's also crucial to keep in mind that, even though each of these widely used protocols may be based on an industry radio standard, network protocols are instead industry alliances rather than standards[7]. The partnerships are in place to encourage protocol adoption and ensure interoperability. Membership in the alliance is necessary to promote and sell goods that employ these standards. This also explains why new variations of these protocols appear to be aiming for the application space that has historically been controlled by others. The most widely used wireless local area network (WLAN) protocol is called Wi-Fi (Wireless Fidelity), and it operates on the 2.4 GHz UHF and 5 GHz ISM frequencies under the IEEE 802.11 standard. Devices that are between 20 and 40 meters from the source of Wi-Fi can access the Internet. The maximum data rate for the 802.11n standard is 600 Mbps, depending on the number of antennas and the channel frequency used.

Wireless protocols have reached capacity limitations due to recent advancements in the Internet of Things, video conferencing, low-latency online gaming, high-definition video streaming, etc. As a result, the 802.11ax wireless protocol was swiftly adopted since it can effectively handle higher client densities thanks to additional channel-sharing functionality utilizing MU-MIMO.

1.2 Motivation

There are several issues with cables and wiring. Installation challenges can include difficulty with digging trenches or scaling poles, issues with aerial cable aesthetics, and backhoes that may unintentionally dig up cables, all of which can result in expensive installation costs. Additionally, the cable could be put in an undesirable location, such as a region with a weak service market. Air also doesn't corrode or collapse in harsh weather, unlike cable and wiring. The fixed networks of wired systems appear to some onlookers, including the operators themselves, as risky high-capital investments in a world of quickly evolving technology.

Also, very high demand related to smart devices and smart home appliances has increased demand for Wi-Fi-enabled devices. The Internet of Things has made the world more connected. Therefore, wireless connectivity will see high demand. Nowadays, almost every device has at least one wireless connectivity medium

1.3 Objective

The objective of this analysis is to conduct a comprehensive examination of WLAN IEEE standards, specifically 802.11n, in comparison to legacy standards 802.11g, 802.11b, and 802.11a. The research aims to provide a detailed understanding of the technological advancements introduced in 802.11n and how they perform relative to the older standards in terms of data rates, coverage range, and overall network efficiency. By addressing the coexistence of multiple standards, the objective is to offer insights that will guide decisions related to network deployment, device compatibility, and the optimal utilization of wireless resources in diverse WLAN environments.

1.4 Problem Statement

The problem statement for the analysis of WLAN IEEE standards 802.11n over 802.11g, 802.11b, and 802.11a centers on the imperative to discern the comparative performance and technological disparities among these standards. While 802.11n is recognized for its advancements over 802.11g, the concurrent existence of other legacy standards, namely 802.11b and 802.11a, introduces complexity. The challenge lies in systematically evaluating how 802.11n outpaces or aligns with these older standards concerning data rates, range, and efficiency. This investigation is crucial for guiding decisions in network design, device compatibility, and addressing the coexistence of multiple standards within WLAN environments.

1.5 Organization of the Report

This thesis is divided into ten chapters. The first chapters introduce the wireless background and the purpose of the given research. The Second chapter describes the literature review for the wireless domain and research-related work. The third chapter describes Wi-Fi architecture and various Wi-Fi concepts. Chapter four describes generic concepts of device drivers and kernel modules. The fifth chapter explains NXP Wi-Fi Driver-firmware architecture, tasks, and features. The sixth chapter explains tools like bitbucket, jira, and git which are highly useful in daily work. The seventh chapter describes the dev sanity objective. Chapter eight will explain Coverity issues. Chapter Nine explains the process of solving issues related to Wi-Fi. Chapter ten brings methodology for simulating performance in NS3 tools and different simulation scenarios used to produce results. Following by simulation results. Last chapter eleven contains the conclusion and future work.

Chapter 2

Literature Survey

2.1 802.11 Standard

IEEE has published a standard document for understanding 802.11ax[8], 802.11ac[9], 802.11n[10] and older versions.[11] New feature and drawbacks are discussed in [12] for 802.11ax amendment. Unplanned wireless deployment may cause inefficiencies in the network since 11ax can operate on several Gigabits. ”Dynamic Channel Bonding”(DCB) and Orthogonal Frequency Division Multiple Access(OFDMA) was suggested for improvement in spectrum usage efficiency.

[13] gives a thorough analysis of the IEEE 802.11ax standard. The writers discuss the amendment’s prerequisites, scope, and qualities, as well as its need. The importance of the coexistence of the IEEE 802.11ax standard and Long Term Evolution (LTE) is emphasized, along with the challenges posed by the Internet of Things (IoT) scenarios. It is emphasized that the 11ax amendment enables efficient spectrum usage and an enhanced user experience in high-density WLAN networks.

One of the most dependable open-source network simulators, NS-3 has been widely used by both businesses and the research community. Additionally, it has undergone several validation experiments to make sure that its 802.11 models are accurate [14]. These factors led us to select it as a viable option for implementing and testing 802.11ax, 802.11ac, and 802.11n functionalities.

Ravindranath [15] has demonstrated performance improvements in 802.11ac vs 802.11n. It concluded that 802.11ac (VHT) can achieve data rates of 2.3 Gbps in the 5GHz band. which has been achieved by enhancing features in the 802.11n protocol PHY and MAC layers.

Machrouh [16] has measured the performance of 802.11ax and 802.11ac and concluded that the 11ax amendment can improve throughput by improving efficiency. In [17] Darwish and Mohamed have also discussed the high throughput and efficiency of 802.11 wireless standards. The 802.11 versions simulated in this paper are discussed next. overview of standards is given further in this section.

802.11 wireless networks the definitive guide'[1] has every basic details regarding Wi-Fi protocol. 'Linux Device Driver'[18] has explained every little detail regarding to device driver. Green Frame Aggregation is a power-aware frame aggregation solution for IEEE 802.11n/ac-based wireless networks that was suggested by M. Alaslani[19]. It determines the appropriate AMPDU sub-frame size depending on the quality of the channel. GFA leverages the energy budget associated with the maximum A-MPDU sub-frame size in an efficient manner. GFA is implemented and assessed using a wireless testbed based on Linux. The experimental assessment under different channel circumstances demonstrates that GFA may cut energy usage by a factor of up to six compared to the Linux setup by default. In addition, the findings demonstrate that GFA outperforms static frame scaling in terms of network throughput while preserving end-to-end latency.

Nikhil Karoti[20] has proposed a new method to improve the performance of heterogeneous Li-Fi - Wi-Fi networks by aggregating both Li-Fi and Wi-Fi access points called link aggregation framework. Using an LA-based on SINR (LASINR) algorithm, they evaluated the performance of LA-enabled HLWN with typical indoor access networks such as hybrid LiFi-WiFi, standalone WiFi, and standalone LiFi.

In order to further improve the quality of service (QoS) and average data rate performance of LA-enabled HLWN, an intuitive LA for improvement of the QoS (LA-EQoS) algorithm has been developed. The IEEE 802.11n amendment aspires to reach a medium access control (MAC) layer throughput greater than 100 Mbps. It provides two frame aggregation techniques to increase the basic 802.11 MAC layer's efficiency. However, the IEEE standards do not define the scheduler for these methods, leaving it to the discretion of the manufacturer. [21] gives a comprehensive simulation investigation of various aggregation techniques and a basic frame aggregation scheduler, which is shown in Figure 2.1. Method for selecting the aggregated frame size and aggregation method based on a number of relevant characteristics.

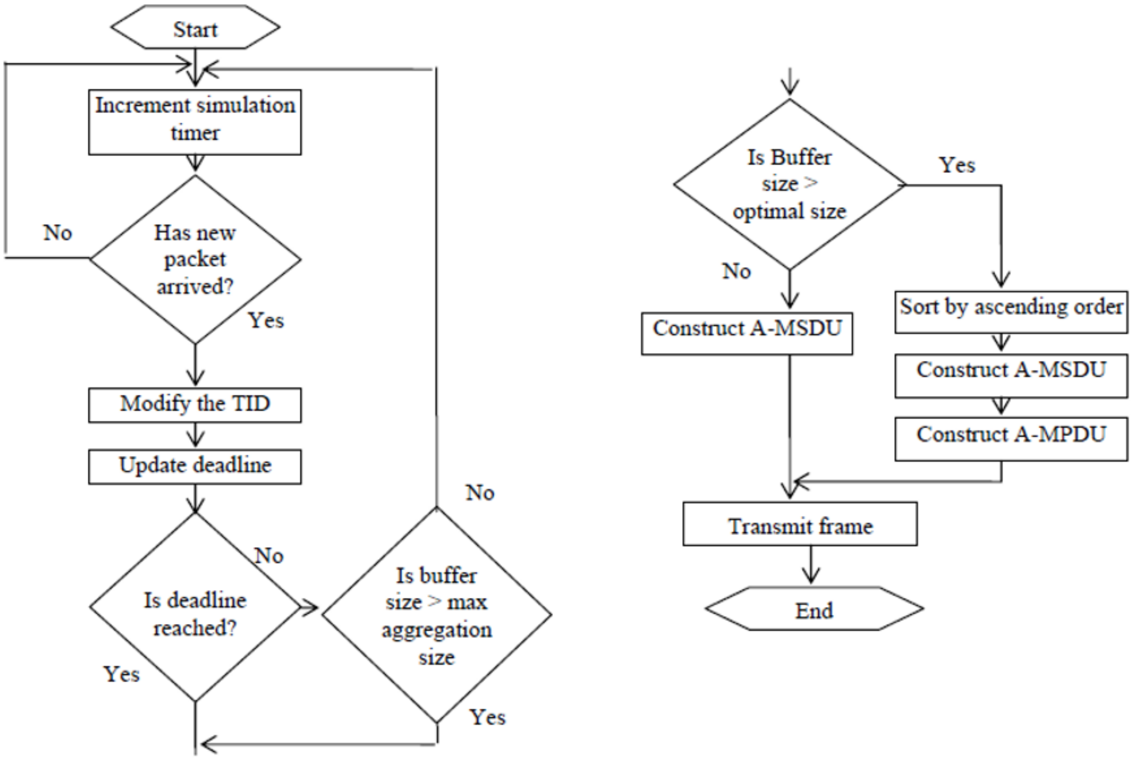

Figure 2.1: Aggregation Flowchart

2.2 802.11 Protocol Stack

This section explains 802.11 Protocol stacks in detail. It describes two levels of OSI layers used by the 802.11 Protocol. PHY layer and MAC layer. 802.11 Protocol mostly added enhancements in these two layers.

2.2.1 PHY layer enhancements

1. Multi-Input Multi-Output:

Multi-Input Multi-Input, Multi-Output (MIMO) is a versatile technology that may be used in several ways. On one end we have spatial multiplexing, while on the other end, we have a transmitter and/or receiver diversity. In the case of pure transmitter/receiver diversity, multiple antennas are used to transmit and receive identical data streams. The existence of many copies of the data reduces the likelihood of mistakes occurring. This enhances the resilience of the connection. In spatial multiplexing, the same bandwidth is utilized to simultaneously transmit multiple data streams in both directions. The data in each data stream is distinct. Here, the data transfer rate is increased[1].

2. Channel Bonding:

   By combining two neighboring 20 MHz channels into a single 40 MHz channel, the potential data rate may be increased by double. Utilizing adjacent channels concurrently, this strategy has previously been used to boost throughput. Each channel is modulated individually and then concatenated at the far end[1].

3. Guard Interval:

   Guard Interval is the interval between symbols that are broadcast. 802.11n employs complicated modulation methods (i.e., Orthogonal Frequency Division Multiplexing - OFDM) in which blocks of input data are encoded into a single OFDM signal. To attain a high level of performance, the symbol must arrive at the receiver without interference or noise, ensuring effective decoding and fewer mistakes[1]. Intersymbol interference occurs when the delay between distinct RF pathways to the receiver exceeds the guard interval, allowing a reflection of the preceding symbol to interfere with the present symbol's signal.

4. Transmit Beam Forming:

   Transmit Beam Forming is a MIMO method used in WLAN chipsets to increase the Signal-to-Noise Ratio (SNR) at the receiver. The existence of numerous signals at the client end of an 802.11 network boosts the downlink SNR and data throughput[1]. This improves system performance and decreases coverage gaps.

5. Modulation and Coding Schemes:

   Radio systems have to adapt to the signal and noise characteristics of the RF path and they accomplish this by changing the modulation rate. Here in table 2.4,

Table 2.1: Modulation and Coding Scheme Index 11n, 11ac, and 11ax

MCS Index			**Spatial Stream**	**Modulation**	**Coding**
HT	**VHT**	**HE**			
0	0	0	1	BPSK	1/2
1	1	1	1	QPSK	1/2
2	2	2	1	QPSK	3/4
3	3	3	1	16-QAM	1/2
4	4	4	1	16-QAM	3/4
5	5	5	1	64-QAM	2/3
6	6	6	1	64-QAM	3/4
7	7	7	1	64-QAM	5/6
	8	8	1	256-QAM	3/4
	9	9	1	256-QAM	5/6
		10	1	1024-QAM	3/4
		11	1	1024-QAM	5/6

the receiver SNR is the deciding factor for the transmitter's modulation with a view to optimizing the data and error rates. At any point, modulating for a higher data rate will increase the error rate and at some point, the increased error rate will decrease the overall data throughput. 802.11a and 802.11gstandards adopted a method called OFDM. OFDM divides a radio channel, into smaller ones, each with its own subcarrier signal. For 802.11a and 802.11g, the symbol period is 4 uS, with a guard interval of 800 nS. At the maximum data rate, 54 Mbps, each symbol carries 216 data bits. These data bits are spread out over 48 subcarriers[1]. 72 error correction bits were transmitted in each symbol at 54 Mbps, resulting in 288 bits in the symbol. To squeeze these many bits on each subcarrier, the subcarrier is modulated using 64 QAM or Quadrature Amplitude Modulation. This means that each subcarrier is able to carry 6 bits (a combination of data and error correction bits).

2.2.2 MAC layer enhancements

Frame aggregation and block ACK or acknowledgment are supported in both 802.11n and 11ac standards.

1. Frame Aggregation:

   Every time a client/AP desires to transmit in a frame, it competes for a chance to do so in the medium, resulting in contention, collision, and back-off delays. 802.11n contains techniques for stations to aggregate frames.

Using MAC-layer aggregation, a station having many frames to broadcast has the option of combining them into a single aggregate frame (MAC MPDU)[1]. The resultant frame has fewer headers than it would without aggregation, and since fewer, bigger frames are sent, contention time on the wireless medium is decreased. Due to the cost of headers and inter-frame gaps, the efficiency of transfer decreases with decreasing frame length.

Aggregated MSDU (A-MSDU) and Aggregated-MAC Protocol Data Unit (A-MPDU) are two aggregation strategies that minimize each frame's overhead to a single radio preamble. Legacy ACKs may be used to confirm Aggregated MSDUs, while Aggregated MPDUs need Block ACKs.

2. Block ACK:

   In older 802.11 a/b/g systems, the receiving station confirms the receipt of each non-multicast/broadcast frame by sending an acknowledgment (ACK frame) to the transmitting station nearly immediately. If this ACK frame is not received, the transmitter will retransmit until it is. The ACK method increases 802.11's resiliency and assures that all sent frames eventually reach the receiver. The inclusion of an ACK frame to every sent frame, however, lowers the efficiency of the protocol. This is remedied by the block acknowledgment mechanism, which transmits a single block ACK packet in response to many received frames[1], so increasing both efficiency and throughput. This technique aggregates the ACKs of separate frames from MPDU aggregation into a single frame that is returned to the transmitter by the receiver. Therefore, only the unacknowledged frames may be retransmitted. Compared to MSDU aggregation, this selective retransmission utilizing MPDU aggregation is very successful in noisy situations.

2.3 802.11b

The IEEE 802.11b standard, ratified in 1999, represents a significant milestone in the development of wireless networking technology. Operating within the 2.4GHz frequency band, 802.11b introduced key features that contributed to the widespread adoption of Wi-Fi. With a maximum theoretical data rate of 11 Mbps, this standard marked a notable improvement over its predecessor, 802.11a, which operated in the 5GHz band.

A foundational document in the establishment of 802.11b is the IEEE Std 802.11b-1999, where technical specifications, protocols, and design principles are outlined. Leveraging Direct Sequence Spread Spectrum (DSSS) modulation for data transmission, 802.11b offered an accessible solution for wireless connectivity, catering to the growing demand for efficient networking solutions in various settings.

What set 802.11b apart was its strategic backward compatibility, allowing for a smooth integration process with existing network infrastructures. This backward compatibility feature enabled a phased upgrade approach, accommodating 802.11b-enabled devices without requiring an immediate overhaul of networking equipment.

The standard gained popularity due to its affordability, accessibility, and compatibility, meeting the increasing demand for wireless connectivity in homes, businesses, and educational institutions. However, 802.11b faced challenges related to potential interference from devices operating in the 2.4GHz band, such as cordless phones and microwaves, impacting network performance. The shared frequency band also introduced concerns about congestion in environments with a high density of wireless devices.

Despite these challenges, the legacy of 802.11b endures through its impact on subsequent Wi-Fi standards. Its backward compatibility feature remains a testament to its lasting influence on the evolution of wireless communication technologies. In essence, the introduction of 802.11b marked a crucial step in making wireless networking more accessible and laid the groundwork for the interconnected digital landscape we navigate today.

2.4 802.11a

The IEEE 802.11a standard, ratified in 1999, represents a pioneering advancement in wireless networking technology, offering a critical foundation for the evolution of Wi-Fi. Operating in the 5GHz frequency band, 802.11a introduced key features that differentiated it from its predecessor, 802.11b. This standard, documented in IEEE Std 802.11a-1999, marked a departure from the congested 2.4GHz band, aiming to provide improved performance and reduced interference.

Characterized by Orthogonal Frequency Division Multiplexing (OFDM) modulation, 802.11a offered a maximum theoretical data rate of 54 Mbps, a substantial leap in comparison to the 11 Mbps offered by 802.11b. The higher frequency band and advanced modulation techniques contributed to increased channel capacity and reliability, making it an attractive choice for applications demanding higher data transfer rates.

802.11a's deployment faced challenges related to its higher frequency, such as reduced signal range and penetration through obstacles. However, in environments where these limitations were less critical, it provided a more robust and efficient solution for wireless communication.

The standard's strategic departure from the 2.4GHz band alleviated issues related to interference from common household devices. This departure, along with the incorporation of more non-overlapping channels, contributed to a reduction in contention and improved the overall performance of wireless networks.

Despite its early challenges and the subsequent dominance of 802.11b in the consumer market, the legacy of 802.11a persists in several ways. Its introduction laid the groundwork for subsequent standards, influencing the development of more advanced Wi-Fi iterations. Furthermore, the 5GHz frequency band, initially championed by 802.11a, has become integral in modern Wi-Fi deployments, especially with the advent of dual-band and tri-band routers.

In essence, the introduction of the 802.11a standard marked a critical phase in the evolution of wireless networking, offering enhanced performance and paving the way for the high-speed, reliable Wi-Fi connectivity we experience in today's interconnected world.

2.5 802.11g

The IEEE 802.11g standard, introduced in 2003, stands as a pivotal advancement in wireless networking technology, bridging the gap between its predecessors and future Wi-Fi iterations. Operating in the widely used 2.4GHz frequency band, 802.11g represented a significant enhancement over the existing 802.11b standard. This standard, documented in IEEE Std 802.11g-2003, aimed to combine the best aspects of 802.11a's data rates and 802.11b's widespread popularity.

802.11g utilized Orthogonal Frequency Division Multiplexing (OFDM) modulation, akin to 802.11a, but within the 2.4GHz frequency, thereby providing a maximum theoretical data rate of 54 Mbps. This marked improvement in data rates addressed the growing demand for higher bandwidth in both home and business environments, facilitating smoother multimedia streaming, file transfers, and online activities.

One of the distinctive features of 802.11g was its backward compatibility with 802.11b, allowing a seamless integration process for existing networks. This characteristic eased the transition for users, enabling them to upgrade to 802.11g gradually without rendering their 802.11b devices obsolete.

Despite its advancements, 802.11g faced challenges related to potential interference in the crowded 2.4GHz band, similar to those experienced by its predecessor. However, its improved data rates and compatibility ensured its widespread adoption in consumer and enterprise settings, further establishing Wi-Fi as a mainstream technology.

The introduction of 802.11g marked a critical phase in the evolution of wireless networking, catering to the increasing demand for faster and more reliable wireless connectivity. Its influence is still evident today, as the standard's compatibility features and data rate advancements laid the groundwork for subsequent Wi-Fi standards, contributing to the seamless integration and evolution of wireless technology in our interconnected world.

2.6 802.11n

802.11n appeared at an important time in 802.11's development. Prior PHYs were intended for a certain radio spectrum[22]. Only in the 2.4 GHz ISM band was the first 802.11 frequency-hopping and direct-sequence PHYs described.

Table 2.2: Main 802.11n Specification

Maximum data rate	600 Mbps
RF Band	2.4 and 5 GHz
Highest modulation	64-QAM
Guard band	0.4μs, 0.8μs
Channel width	20, 40 MHz

When the 5 GHz spectrum was made available for unlicensed usage, 802.11a was developed. The goal of 802.11g was to make the 802.11a technology available in the 2.4 GHz range. However, 802.11n was developed while both bands were accessible. As shown in Table 2.2 maximum data rate of 802.11n is 600 Mbps. The highest modulation is 64-QAM which is the MCS-7 standard. 0.4 and 0.8 μs guard band it is using. Also supports 20 and 40 MHz channel Bandwidth.

802.11n is backward compatible with the legacy 802.11a/b/g format. High throughput(HT) is defined for its latest developed Physical layer convergence protocol thus it can operate in two modes: mixed mode(802.11a/b/g and n) and Greenfield mode(802.11n).[22] it can support up to four spatial streams. while only 20 and 40Mhz channel bonding is supported. Though at that time 5Ghz band was newly supported thus very less interference was faced and higher throughput was achieved.

The MAC's efficiency is just something that 802.11n spends a lot of time working to improve. Although many users of 802.11 equipment pay attention to the high data rates, the increased efficiency is a significant factor in the speed increases. Frame aggregation is the key 802.11n approach for increasing efficiency. Frame aggregation divides the expense of each transmitter's access to the medium over several smaller frames. Aggregation can increase efficiency by 50% to around 75%, depending on the type of data being conveyed.

2.7 802.11ac

As shown in Table 2.3 maximum data rate of 802.11ac is 2.3 Gbps which enables high-definition video streaming. The highest modulation is 256-QAM which is the MCS-9 standard. 0.4 and 0.8 μs guard band it is using. Also supports 20, 40, 80, and 160 MHz channel Bandwidth. It was developed in 2008 and was approved in its entirety in January 2014 by IEEE[23].

Table 2.3: Main 802.11ac Specification

Maximum data rate	2.3 Gbps
RF Band	5 GHz
Highest modulation	256-QAM
Guard band	0.4μs, 0.8μs
Channel width	20, 40, 80, 160 MHz

Physical speeds greater than 500 Mb/s are supported by this version of 802.11 for a single connection. Multi-user MIMO, which can support up to four clients, larger channels, which can support up to 160 MHz bandwidth, and higher-density modulation, which can support up to 256-QAM are some of the major changes that have been made to 802.11ac to enable such a high data rate. It can support up to eight spatial streams.

802.11ac is not a revolutionary new technology; rather, it is an enhancement on its predecessor, 802.11n. Following the introduction of MIMO, the majority of the techniques used to increase speed in 802.11ac have become common knowledge. In contrast to 802.11n, which generated substantial new MAC characteristics in order to boost efficiency, 802.11ac builds on already-known techniques and takes them to a new level[23]. However, there is one notable exception to this rule. Instead of just boosting the number of data streams that are delivered to a single client, the multi-user variation of MIMO that is being introduced by 802.11ac makes it possible for an access point (AP) to transmit to several clients at the same time.

2.8 802.11ax

802.11ax is the latest amendment in the WLAN protocol. It has made changes in the physical layer for improvement. As shown in Table 2.4 maximum data rate of 802.11ax is 9 Gbps. The highest modulation is 1024-QAM which is the MCS-11 standard. 0.8, 1.6, and 3.2 μs guard band it is using. Also supports 20, 40, 80, and 160 MHz channel Bandwidth[24]. It also has backward compatibility with the older 802.11a/b/g/n/ac protocol.

It has two modes of operation single-user mode and multi-user mode. In single-user mode, sequential data can be transferred after securing access to media and simultaneous transmission can occur in multi-user mode. This mode is further divided by the standard into Down-link and Up-link Multi-user. The foundation of the multi-user downlink is the data that the Access Point transmits simultaneously for a number of connected wireless Stations.

802.11ax is also called HE (Higher efficiency) as it utilizes radio frequency more efficiently. The main goal for development for 11ax was better traffic management. Most of the 802.11ax upgrade is at the physical layer which involves OFDM with a multi-user feature whereas older 11n/ac uses OFDM with a single user. Another significant improvement is from the access point(AP) side which can monitor both uplink and down-

Table 2.4: Main 802.11ax Specification

Maximum data rate	9 Gbps.
RF Band	2.4 or 5 GHz.
Highest modulation	1024-QAM
Guard band	0.8μs, 1.6μs, 3.2μs.
Channel width	20, 40, 80, 160 MHz

link transmission to multiple clients. Along with that protocol is backward compatible with older standards and operates on both 2.4Ghz and 5Ghz while 802.11ac can only operate on 5Ghz bands.

Both 802.11ac and 802.11ax access points may receive and deliver data concurrently to multi-users (MU) using functionalities provided by multilink MU-MIMO. This functionality gives access points the freedom to serve user clients in their immediate vicinity. Orthogonal Frequency Division Multiple Access(OFDMA) and multi-user MIMO are the techniques employed in both protocols. 802.11ax is also capable of Transmit beam forming which is the technique of MIMO that improves SNR at receiver[24]. Overall basic feature comparison of 802.11n 802.11ac and 802.11ax is given in table 2.5

Table 2.5: Basic Feature Comparison of 802.11n 802.11ac and 802.11ax

	802.11n (Wi-Fi 4)	**802.11ac (Wi-Fi 5)**	**802.11ax (Wi-Fi 6)**
Frequency bands	2.4 GHz and 5 GHz	5 GHz only	2.4 GHZ, 5 GHz
Channel size (MHz)	20,40	20, 40, 80, 80 + 80, and 160	20, 40, 80, 80+80, and 160
Frequency multiplexing	OFDM	OFDM	OFDM and OFDMA
OFDM symbol Time (us)	3.2	3.2	12.8
Guard interval (us)	.04 or .08	.04 or .08	.08, 1.6, or 3.2
Total symbol time (us)	3.6 or 4.0	3.6 or 4.0	13.6, 14.4, or 16.0
Modulation	Binary Phase-Shift Keying (BPSK), Quadrature Phase-Shift Keying (QPSK), 16-QAM, 64-QAM	BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM	BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM, 1024-QAM
MU-MIMO	N/A	DL	DL and UL
OFDMA	N/A	N/A	DL and UL

Chapter 3

Wi-Fi

In this chapter, some general concepts of Wi-Fi are explained like Wi-Fi Architecture, MAC Layer, physical layer, Frame structure, etc, and some advanced concepts like Frame Aggregation, Also some workflow platforms like Jira, Bitbucket, Git, etc.

3.1 Wi-Fi Architecture

There are four primary physical components that make up an 802.11 network:

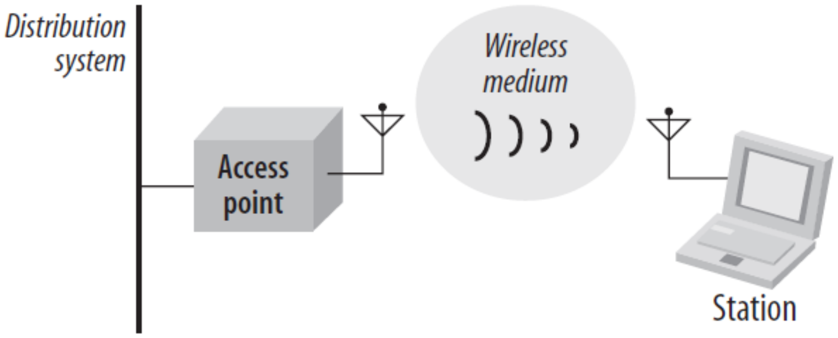

Figure 3.1: Wi-Fi Architecture [1]

Station (STA):

Any device that has a MAC and PHY interface that complies with 802.11 standards may connect to the wireless medium (WM).

Access points (AP):

Any organization that has station capability and offers related STAs access to distribution services via the use of wireless media is considered a distribution service provider.

Wireless medium:

The architecture permits many physical layers to support 802.11 MAC. At first, there were two radio frequency (RF) layers and one infrared layer, but RF layers are more common. RF layers have also been standardized.

Distribution system:

A system that is used to build an extended service set by interconnecting a series of basic service sets and integrated local area networks (LANs) (ESS).

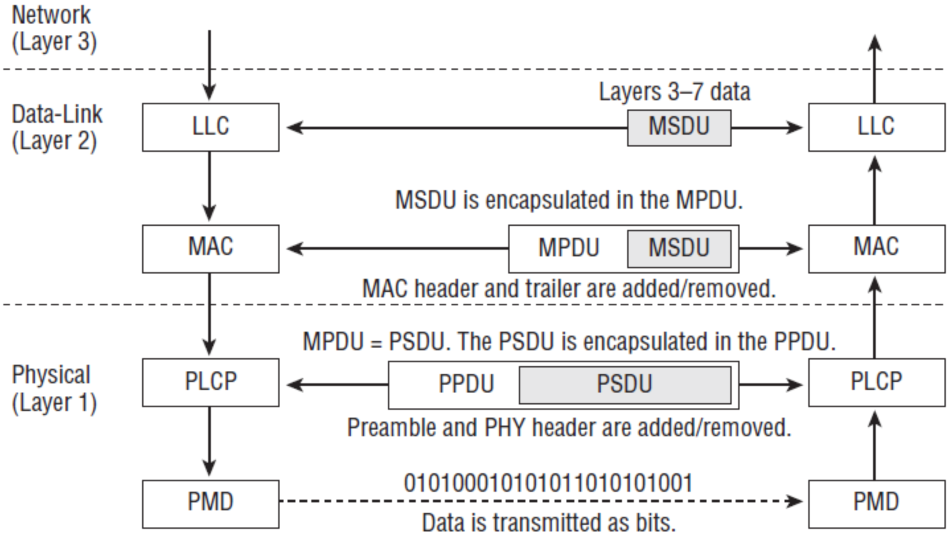

Figure 3.2: Data Link and Physical Layer [1]

The 802.11 Data-Link layers are divided into two sublayers:

- While not all IEEE 802 networks make use of it, the top part is the IEEE 802.2 Logical Link Control (LLC) sublayer, which is universal across all 802-based systems.

- All 802.11 networks have a common MAC sublayer at the Data-Link layer's foundation. The 802.11 protocol standardizes the MAC layer's procedures. Between the lower PHY layer and the higher LLC sublayer is the media access control (MAC) sublayer.

3.1.1 MAC Layer

Only the physical layer and the Media Access Control (MAC) sublayer of the Data-Link layer of the OSI architecture are defined by the IEEE 802.11-2007 standard. Although there are QoS interactions between the top OSI levels and the 802.11 MAC sublayer, these layers were not intended to be covered by the 802.11 standards.

MSDU:

802.11ac is an upgrade over 802.11n, not a fundamental shift. Many of the techniques used to increase speed in 802.11ac are widely known now that MIMO has been introduced. With one exception, 802.11ac improves upon tried-and-true techniques, as opposed to 802.11n, which introduced major new MAC features to boost efficiency. In contrast to previous MIMO implementations that simply increased the amount of data streams available to a single client, 802.11ac's multi-user MIMO variation enables an access point (AP) to provide data to several clients simultaneously.

MPDU:

Before transmitting the MSDU to the MAC sublayer, the LLC adds the MAC header. MSDU now includes MAC PDU (MPDU). MPDUs are 802.11 frames. Figure 1.1 shows that an 802.11 frame has a layer 2 MAC leader, a variable-length frame body, and a 32-bit CRC termed the frame check sequence.

3.1.2 Physical Layer

Like the Data-Link layer, the physical layer (PHY) has two sublayers. Physical layer sublayers include PLCP and PMD. The PLCP sublayer creates a PLCP Protocol Data Unit after receiving a frame from the MAC sublayer (PPDU). PMD modulates and transmits bits.

PSDU:

Any door may be entered or exited. From each side, the entrance goes to the same area. The PLCP Service Data Unit is the MPDU's opposite (PSDU). MAC calls an 802.11 frame an MPDU, whereas the physical layer calls it a PSDU. The sole difference is whether you're looking at the door from the inside or outside or the physical or logical OSI layer.

PPDU:

The PLCP generates the PLCP Protocol Data Unit after receiving the PSDU. PLCP adds the PSDU preamble and PHY header. 802.11 radios require the preamble to keep in sync. The PMD sublayer modifies the PPDU before delivering data bits.

3.2 802.11 Frames

The three kinds of 802.11 frames are management, control, and data. Frames with management information are used to manage the BSS, frames with control information are used to manage access to the medium, and frames with data information (layers 3-7) comprise the payloads. In the process of exchanging frames, we will pay more attention to the information contained inside each frame than we will to its surrounding context. The three main components of an 802.11 frame are the header, the data, and the trailer.

There is a predetermined sequence to information in every frame that adheres to the MAC frame standard. Below figure 3.3 shows the general 802.11 frame format. All frames, including reserved kinds and subtypes, include the first three fields (Frame Control, Duration/ID, and Address 1) and the final field (FCS), which together make up the minimum frame format. Only specific frame types and subtypes have the fields Address 2, Address 3, Sequence Control, Address 4, QoS Control, HT Control, and Frame Body.

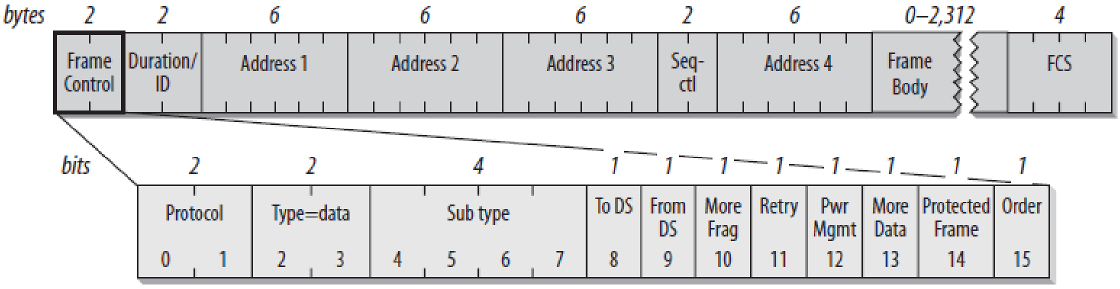

Figure 3.3: 802.11 General Frame Structure [1]

Management Frames:

A collection of management frames is used to administer the BSS. The BSS is subject to clients probing it, associating with it, roaming away from it, and being detached from it. As was just shown to you, the frame control field of the header must include a type 0 for management frames to be sent.

Table 3.1: Different Types of Management Frames[1]

Subtype Field	Description
0000	Association request
0010	Reassociation request
0100	Probe request
0110	Timing advertisement
1000	Beacon
1010	Disassociation
1100	Deauthentication
1011	Authentication
1110	Action
0001	Association response
0011	Reassociation response
0101	Probe response
0111	Reserved

Control Frames:

A control frame might be used to recognize a previous frame or to restrict access to the media. There's no actual data in control frames; just a header and a trailer. Only point coordination function (PCF) based wireless networks use the control frame types that are bolded in the table below. Unfortunately, these ideas were never put into practice.

Table 3.2: Different Types of Control Frames[1]

Subtype Field	Description
0100	Beamforming Report Poll
0101	VHT/HE NDP Announcement
0110	Control Frame Extension
0111	Control wrapper
1000	Block ACK Request
1001	Block ACK
1010	PS-Poll
1011	RTS
1100	CTS
1101	ACK
1110	CF-End
1111	CF-END+CF-ACK
0111	Reserved

Data Frames:

To transmit information or start an event, data frames are employed. Some data frames are ”null data frames,” meaning they simply have a header and trailer. Only point coordination function (PCF) or HCF controlled channel access (HCCA) based wireless networks employ the data frame types in the table below that are bolded. In the actual world, they were never used. There are now just 4 to focus on.

Table 3.3: Different Types of Data Frames[1]

Subtype Field	**Description**
0100	Beamforming Report Poll
0101	VHT/HE NDP Announcement
0110	Control Frame Extension
0111	Control wrapper
1000	Block ACK Request
1001	Block ACK
1010	PS-Poll
1011	RTS
1100	CTS
1101	ACK
1110	CF-End
1111	CF-END+CF-ACK
0111	Reserved

3.3 Frame Aggregation

With the approval of the 802.11n amendment, 802.11 gained two new types of frame aggregation.

1. Aggregate MAC Service Data Unit (A-MSDU)
2. Aggregate MAC Protocol Data Unit (A-MPDU)

Through the use of frame aggregation, it is possible to aggregate a number of smaller MSDUs or MPDUs into a single frame, hence reducing the amount of overhead that would have been necessary for each individual frame.

As will be seen in the following example, an A-MSDU is composed of a number of A-MSDU subframes. Each A-MSDU subframe consists of a header for an A-MSDU subframe, an MSDU, and anywhere from 0 to 3 octets of padding. Every A-MSDU subframe, with the exception of the very last one, has its length padded to ensure that it

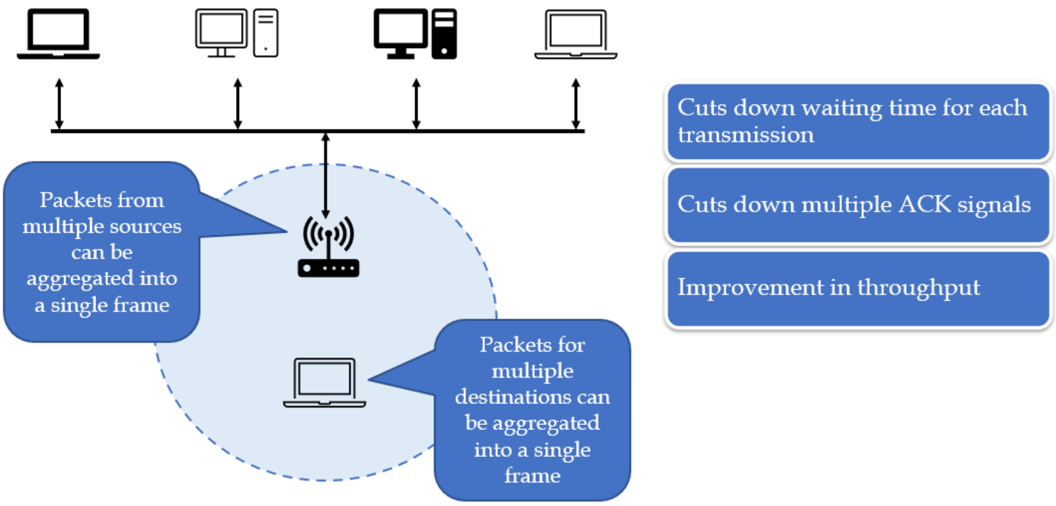

Figure 3.4: Simple Understanding of Frame Aggregation

is a multiple of 4 octets throughout its whole. The final version of the A-MSDU subframe does not include any padding.

A-MSDU Operation

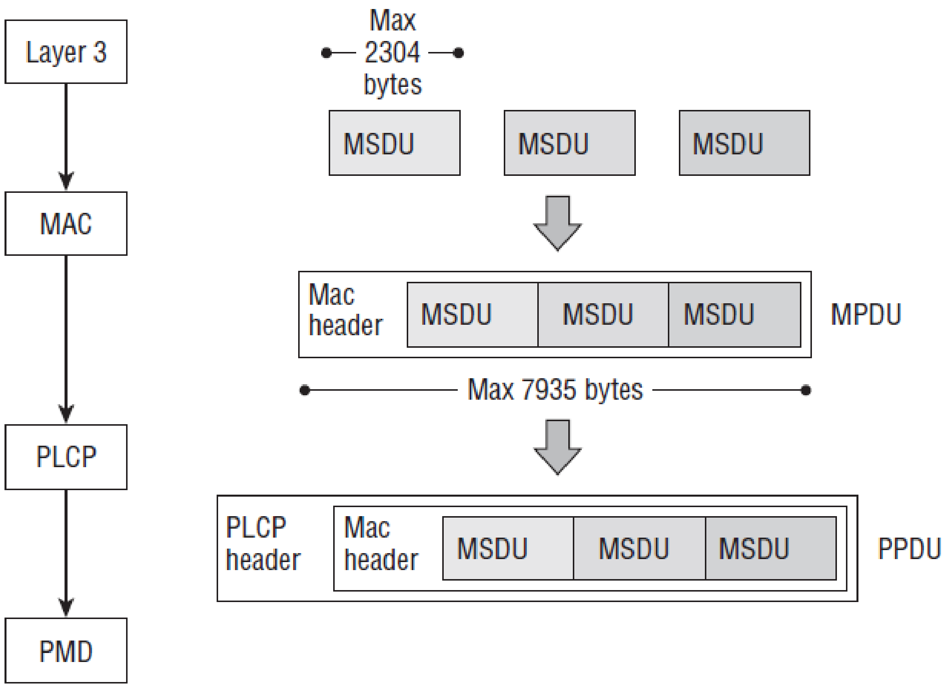

Figure 3.5: A-MSDU Frame Aggregation [1]

If encryption is turned on, each and every MSDU will be encoded together as a single payload. An A-MSDU may only include MSDUs if their DA and SA parameter values match to the same RA and TA values as those MSDUs already contained in it. All of the MSDUs that make up an A-component need to have the same value for their priority parameter. A-MSDUs are required to be sent without being fragmented while contained inside a single QoS data MPDU. The Address 1 field of an MPDU that is transporting an A-MSDU must be set to a value that is distinct from any other address. Both standard data MPDUs carrying MSDUs (or fragments thereof) with the same TID and quality of service data MPDUs carrying A-MSDUs are subject to the same regulations regarding channel access.

The transmission of MPDUs of up to a maximum length of 4095 octets may be accomplished via the use of A-MPDU aggregation. A-MSDUs are not able to be disassembled. It is not possible to send A-MSDUs in an A-MPDU if they are larger than 4065 octets (4095 octets less the QoS data MPDU overhead).

A-MPDU Operation

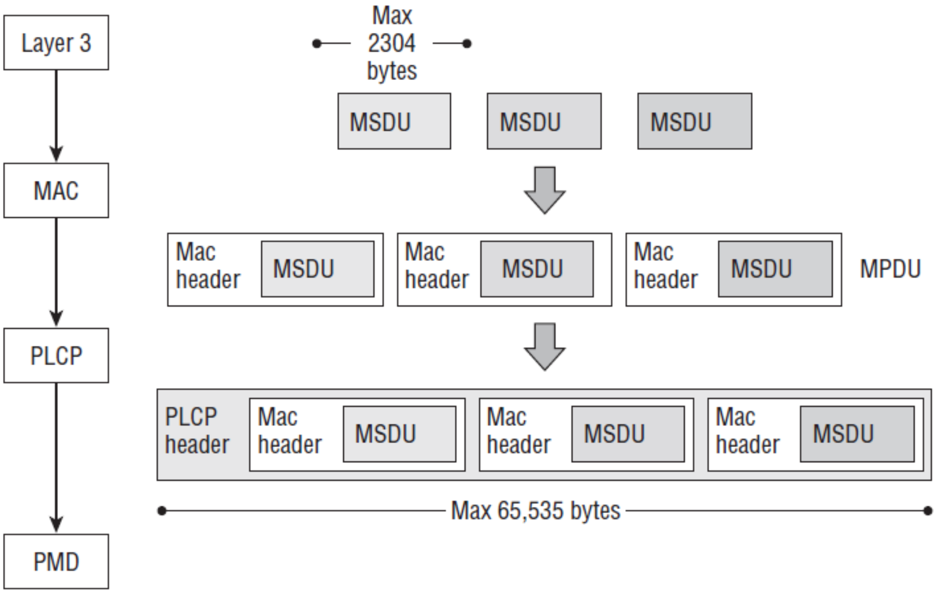

Figure 3.6: A-MPDU Frame Aggregation [1]

If encryption is turned on, each MPDU undergoes its own unique encryption process. An individual recipient address is required for every MPDU included inside an A-MPDU. Every single MPDU has to be a part of the very same 802.11e QoS access category. Block Ack is also necessary for the A-MPDU protocol. The Duration and ID fields in the MAC headers of an A-MPDU have an identical value for each and every MPDU that makes up the A-MPDU. Every protected MPDU that is included inside an A-MPDU has the same Key ID.

Chapter 4

Comparision of 802.11n and Wi-Fi legacy standard

4.1 Data Rates

One of the defining features of 802.11n is its remarkable improvement in data rates compared to legacy standards. While early standards like 802.11b and 802.11a offered maximum data rates of 11 Mbps and 54 Mbps, respectively, 802.11n pushed the boundaries significantly. Through the implementation of Multiple Input Multiple Output (MIMO) technology, 802.11n supports multiple spatial streams, resulting in theoretical maximum data rates of up to 600 Mbps or more. This substantial increase in data rates enhances the network's capacity to handle bandwidth-intensive applications, such as high-definition video streaming and online gaming.

4.2 Range and Coverage

802.11n demonstrates notable advancements in range and coverage compared to legacy standards. The introduction of MIMO technology enables improved signal propagation and reception through the use of multiple antennas. This leads to better coverage and reduced dead spots within the wireless network. In contrast, legacy standards like 802.11b and 802.11g, operating in the 2.4GHz frequency band, may face limitations in range due to potential interference and obstacles.

4.3 Channel Width and Spectrum Efficiency

Legacy Wi-Fi standards typically operate with a 20MHz channel width, which can lead to channel congestion in environments with numerous Wi-Fi devices. 802.11n addresses this challenge by introducing the option of channel bonding, allowing for wider channel widths, such as 40MHz. This increased channel width enhances data rates and spectrum efficiency. However, it's important to note that wider channel widths also mean fewer non-overlapping channels, potentially leading to co-channel interference in densely populated areas.

4.4 Backward Compatibility

Backward compatibility is a critical consideration in the evolution of Wi-Fi standards. 802.11n ensures compatibility with legacy standards, including 802.11b and 802.11g. This means that devices adhering to earlier standards can coexist within an 802.11n network. While this backward compatibility is advantageous for seamless integration, it's essential to recognize that the overall network performance may be limited to the capabilities of the legacy devices.

4.5 Coexistence with Other Networks

As the number of Wi-Fi networks continues to grow, the ability to coexist peacefully with neighboring networks becomes crucial. Legacy Wi-Fi standards, especially those operating in the 2.4GHz band, may experience interference from neighboring networks and non-Wi-Fi devices. In contrast, 802.11n's ability to operate in both 2.4GHz and 5GHz bands provides more flexibility in choosing channels with less interference, contributing to improved coexistence in crowded areas.

4.6 Security Enhancements

Security is a paramount concern in wireless communications. While security mechanisms like WEP and WPA were common in legacy standards, 802.11n builds on these with the implementation of WPA2 (Wi-Fi Protected Access 2) as the standard security protocol. WPA2 provides stronger encryption and advanced security features, enhancing the overall security posture of wireless networks.

Chapter 5

Conclusion

The exploration of WLAN IEEE Standard 802.11n in comparison to legacy Wi-Fi standards unveils a transformative narrative, delineating advancements that have redefined the landscape of wireless communication. This comprehensive analysis, spanning key dimensions such as data rates, range, channel width, backward compatibility, coexistence, and security, provides nuanced insights into the evolution of Wi-Fi technologies, emphasizing the monumental impact of 802.11n.

5.1 Paradigm Shift in Data Rates

The most conspicuous evolution witnessed in this analysis pertains to data rates. IEEE 802.11n's groundbreaking integration of Multiple Input Multiple Output (MIMO) technology has shattered previous limitations, propelling theoretical data rates to unprecedented levels. This paradigm shift is not merely about faster downloads but signifies a fundamental enabler for the modern digital era. The ability to seamlessly support bandwidth-intensive applications has become a cornerstone in the user experience, from multimedia streaming to cloud-based collaboration.

5.2 Range and Coverage Redefined

802.11n's advancements in range and coverage, attributed to the strategic utilization of MIMO, mark a departure from the historical challenges of signal degradation and dead zones. The extended coverage footprint addresses longstanding issues, particularly in dynamic environments where seamless mobility and pervasive connectivity are imperative. This redefinition of range is pivotal in realizing the vision of ubiquitous wireless connectivity, ensuring a more reliable and consistent user experience across diverse settings.

5.3 Channel Width, Spectrum Efficiency, and Coexistence Challenges

The analysis delves into the intricacies of channel width and spectrum efficiency, emphasizing the innovative introduction of channel bonding. While wider channels enhance data rates, the study recognizes the delicate balance required to mitigate co-channel interference. The challenge lies in effective channel planning, ensuring that the benefits of increased bandwidth do not succumb to the potential drawbacks of spectral congestion. This nuanced consideration is critical in urban landscapes where multiple Wi-Fi networks coexist, demanding adaptive and intelligent spectrum utilization strategies.

5.4 Backward Compatibility Dynamics

The study underscores the importance of backward compatibility, acknowledging its role in facilitating a seamless transition to 802.11n. The ability to coexist with legacy Wi-Fi standards ensures a pragmatic approach to network upgrades. However, it also prompts consideration of the performance limitations imposed by legacy devices. Striking the right balance becomes a strategic imperative, requiring network architects to navigate the complexities of legacy support while harnessing the full potential of 802.11n.

5.5 Security Reinforcements

Security considerations stand as a cornerstone in the conclusions drawn from this analysis. The adoption of WPA2 as the standard security protocol signifies a robust response to evolving cybersecurity challenges. As wireless networks become integral to critical communications and data transmission, the enhanced security features of 802.11n play a pivotal role in fortifying the integrity and confidentiality of wireless transmissions.

The conclusions drawn from the analysis extend beyond the immediate comparison of 802.11n and legacy standards, offering insights into the trajectory of future Wi-Fi standards. The need for higher data rates, extended coverage, efficient spectrum utilization, and resilient security measures will likely continue to shape the evolution of Wi-Fi technologies. Lessons learned from 802.11n emphasize the importance of a holistic approach that embraces technological innovation while remaining attuned to the practical considerations of coexistence, backward compatibility, and cybersecurity. In final reflection, the journey from legacy Wi-Fi standards to IEEE Standard 802.11n encapsulates a narrative of continuous innovation, responding to the dynamic demands of an interconnected world. 802.11n emerges not just as a standard but as a catalyst for reimagining the possibilities of wireless communication. As the digital landscape evolves, with the Internet of Things (IoT) and 5G on the horizon, the insights gleaned from this analysis guide us in navigating the complexities of future wireless ecosystems. The legacy of 802.11n extends beyond its technological attributes; it serves as a beacon illuminating the path toward a connected future characterized by speed, reliability, and security.

Bibliography

[1] M. Gast, *802.11 wireless networks the definitive guide.* Sebastopol, CA: O'Reilly Media, 2 ed., 2005.

[2] U. Cali, M. Kuzlu, M. Pipattanasomporn, J. Kempf, and L. Bai, "Smart grid standards and protocols," in *Digitalization of Power Markets and Systems Using Energy Informatics*, pp. 39–58, Cham: Springer International Publishing, 2021.

[3] B. S. England and A. T. Alouani, "Internet-based advanced metering and control infrastructure of smart grid," *Electr. Eng. (Berl., Print)*, vol. 103, no. 6, pp. 2989–2996, 2021.

[4] V. Muneeswaran, P. Nagaraj, M. P. Rajasekaran, S. U. Reddy, N. S. Chaithanya, and S. Babajan, "Iot based multiple vital health parameter detection and analyzer system," in *2022 7th International Conference on Communication and Electronics Systems (ICCES)*, pp. 473–478, IEEE, 2022.

[5] B. Breve, L. Caruccio, S. Cirillo, V. Deufemia, and G. Polese, "Visual ecg analysis in real-world scenarios.," in *DMSVIVA*, pp. 46–54, 2021.

[6] C. Stolojescu-Crisan, C. Crisan, and B.-P. Butunoi, "An IoT-based smart home automation system," *Sensors (Basel)*, vol. 21, no. 11, p. 3784, 2021.

[7] K. Mangunkusumo, A. Surya, D. Jintaka, and H. Tambunan, "Guidance on communication media selection for advanced metering infrastructure in indonesia," in *2021 3rd International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*, pp. 408–413, IEEE, 2021.

[8] "IEEE standard for information technology–telecommunications and information exchange between systems local and metropolitan area networks–specific requirements

part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications amendment 1: Enhancements for high-efficiency WLAN," tech. rep., IEEE, Piscataway, NJ, USA, May 2021.

[9] "IEEE standard for information technology–telecommunications and information exchange between systems—local and metropolitan area networks–specific requirements–part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) Specifications–Amendment 4: Enhancements for very high throughput for operation in bands below 6 GHz," *IEEE Std 802. 11ac(TM)-2013 (Amendment to IEEE Std 802. 11-2012, as amended by IEEE Std 802. 11ae-2012, IEEE Std 802. 11aa-2012, and IEEE Std 802. 11ad-2012)*, pp. 1–425, 2013.

[10] "IEEE standard for information technology– local and metropolitan area networks– specific requirements– part 11: Wireless LAN medium access control (MAC)and physical layer (PHY) specifications amendment 5: Enhancements for higher throughput," tech. rep., IEEE, Piscataway, NJ, USA, Oct. 2009.

[11] IEEE, *8802.11-99 wireless LAN MAC & phy specifications: Standard for information technology-telecommunications and information exchange between systems-LAN/man-specific requirements-part 11: Wireless LAN medium access control (mac) and physical layer (phy) specifications pt.11*. Piscataway, NJ: I.E.E.E. Press, 1999 ed., 2006.

[12] B. Bellalta, "IEEE 802.11ax: High-efficiency WLANS," *IEEE Wirel. Commun.*, vol. 23, no. 1, pp. 38–46, 2016.

[13] M. S. Afaqui, E. Garcia-Villegas, and E. Lopez-Aguilera, "IEEE 802.11ax: Challenges and requirements for future high efficiency WiFi," *IEEE Wirel. Commun.*, vol. 24, no. 3, pp. 130–137, 2017.

[14] A. Jonsson, D. Akerman, E. Fitzgerald, C. Nyberg, B. E. Priyanto, and K. Agardh, "Modeling, implementation and evaluation of IEEE 802.11ac in NS-3 for enterprise networks," in *2016 Wireless Days (WD)*, IEEE, 2016.

[15] N. S. Ravindranath, I. Singh, A. Prasad, and V. S. Rao, "Performance evaluation of IEEE 802.11ac and 802.11n using NS3," *Indian J. Sci. Technol.*, vol. 9, no. 26, 2016.

[16] Z. Machrouh and A. Najid, "High efficiency IEEE 802.11ax MU-MIMO and frame aggregation analysis," in *2018 International Conference on Advanced Communication Technologies and Networking (CommNet)*, IEEE, 2018.

[17] M. Darwish, M. B. Ali, M. Altaeb, S. O. Sati, and M. S. Elmusrati, "Comparison between high throughput and efficiency of 802.11 wireless standards," in *2022 International Conference on Innovation and Intelligence for Informatics, Computing, and Technologies (3ICT)*, pp. 470–475, IEEE, 2022.

[18] J. McKellar, A. Rubini, J. Corbet, and G. Kroah-Hartman, *Linux Device Drivers*. Sebastopol, CA: O'Reilly Media, 4 ed., 2013.

[19] M. Alaslani, A. Showail, and B. Shihada, "Green frame aggregation scheme for Wi-Fi networks," in *2015 IEEE 16th International Conference on High Performance Switching and Routing (HPSR)*, IEEE, 2015.

[20] N. M. Karoti, S. Paramita, R. Ahmad, V. A. Bohara, and A. Srivastava, "Improving the performance of heterogeneous LiFi-WiFi network using a novel link aggregation framework," in *2022 IEEE Wireless Communications and Networking Conference (WCNC)*, IEEE, 2022.

[21] T. Selvam and S. Srikanth, "A frame aggregation scheduler for IEEE 802.11n," in *2010 National Conference On Communications (NCC)*, IEEE, 2010.

[22] M. M. S. Kowsar and S. Biswas, "Performance improvement of IEEE 802.11n WLANs via frame aggregation in NS-3," in *2017 International Conference on Electrical, Computer and Communication Engineering (ECCE)*, IEEE, 2017.

[23] N. Khalil and A. Najid, "Performance analysis of 802.11ac with frame aggregation using NS3," *Int. J. Electr. Comput. Eng. (IJECE)*, vol. 10, no. 5, p. 5368, 2020.

[24] A. F. Rochim, B. Harijadi, Y. P. Purbanugraha, S. Fuad, and K. A. Nugroho, "Performance comparison of wireless protocol IEEE 802.11ax vs 802.11ac," in *2020 International Conference on Smart Technology and Applications (ICoSTA)*, IEEE, 2020.