Analyzing the Evolution of IEEE 802.11 Wireless Protocols: Key Features and Technological Advancements

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***Abstract*—Wider wireless channels in 802.11 standards, such as 802.11ac's 80 MHz, This paper provides an in-depth analysis of the IEEE 802.11 wireless protocol, categorizing its key features and differentiating its variants, including but not limited to 802.11a, 802.11b, 802.11g, 802.11ac, and 802.11ax. It explores the main technological advancements that have shaped the evolution of these protocols, which has ultimately led to significant improvement wireless communication landscape.**

I. Introduction

The 802.11 protocol, commonly known as Wi-Fi, is a set of IEEE standards that define wireless LAN technologies. This protocol has undergone several iterations, and each variant introduced key technological advancements and features that brought significant improvement in the wireless communication landscape. The upcoming 802.11 evolution focuses on improving the speed, reliability, and efficiency of wireless data transmission. Therefore, the first section of this paper focuses on the key features of IEEE 802.11. The second section focuses on different versions of 802.11 and their differentiating factor. The third section talks about the overall evolution in technology and upcoming anticipated advancements.

II. Key Features of the 802.11 Protocol

The 802.11 protocol, also known as Wi-Fi, enables wireless communication between devices over radio frequencies. It offers different standards, security options, and operates in various frequency bands, thereby facilitating wireless network connectivity. This sections delves into its key features and categorizes them

A. Wider Channels

Wider wireless channels in 802.11 standards, such as 802.11ac's 80 MHz, 160 MHz, and non-contiguous 160 MHz channels, act as high-capacity data pathways that enable faster data transmission, thereby improving network performance [1]. Wider channels provide more room for data to flow, consequently resulting in faster speeds, lower delays, and better performance for data-hungry applications. However, it is essential to note that using these wider channels requires device compatibility consideration, network coexistence, and available wireless spectrum, particularly in crowded environments.

B. Multi-User MIMO

Multi-User MIMO (MU-MIMO), a feature introduced in the 802.11ac Wi-Fi standard, enables wireless access points to simultaneously transmit data streams to multiple client devices, improving network capacity and efficiency. Unlike older Wi-Fi standards, which served one client at a time, MU-MIMO serves multiple clients concurrently, reducing contention, decreasing latency, and enhancing the overall user experience [1]. This technology is especially valuable in environments with numerous connected devices, optimizing spectrum utilization and increasing network throughput. In 802.11n, a device sends multiple data streams to another device using spatial division multiplexing (SDM). In 802.11ac, it employs Downlink Multi-User MIMO (DL MU-MIMO), allowing an access point (AP) with multiple antennas to send data streams simultaneously to multiple client devices. For instance, if the AP has six antennas, and there are clients with different numbers of antennas (e.g., one for STA1, two for STA2, and two

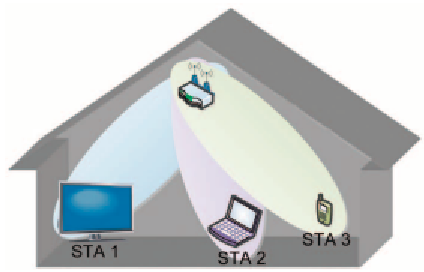

Figure 1. Downlink MIMO example [1]

for STA3), the AP can transmit one stream to STA1, two streams to STA2, and two streams to STA3 at the same time [1]. Figure 1 illustrates this. The key advantage of DL MU-MIMO is that it prevents devices with fewer antennas from monopolizing the network, thus improving overall capacity. However, implementing DL MU-MIMO adds complexity and cost to the network.

C. *Higher Modulation Constellation and increase in Spatial Streams*

The modulation constellation size is increased from 64 QAM (Quadrature Amplitude Modulation) to 256 QAM, allowing for more data to be encoded in each transmission. The increase in the number of spatial streams to eight is aimed at providing enhanced support for DL MU-MIMO.

D. *Packet Aggregation*

The protocol supports packet aggregation, which allows data to be sent in larger chunks [1]. This increases efficiency and can lead to higher data rates.

E. *Physical Layer*

IEEE 802.11 includes various PHY layers, such as FHSS (Frequency Hopping Spread Spectrum), DSSS (Direct Sequence Spread Spectrum), and OFDM (Orthogonal Frequency Division Multiplexing) [2]. FHSS is characterised by rapid switching between different frequencies in a preset sequence. In noisy areas, this helps to reduce interference and enhance dependability. DSSS, on the other hand, uses a specific code sequence to spread the signal over a wider bandwidth. This makes it resistant to some sorts of interference and enables faster data rates. OFDM is a multiplexing technique used in IEEE 802.11a, IEEE 802.11g, and IEEE 802.11n. All of them provide increased overall throughput.

F. *MAC Layer*

IEEE 802.11 uses a contention-based scheme known as Distributed Coordinated Function (DCF), where devices contend for channel access [2]. Another MAC technique known as Point Coordination Function (PCF), where an access point controls when devices can transmit, is included but is less popular than DCF. A Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) mechanism is used to avoid collisions.

G. *Security*

IEEE 802.11 incorporates security mechanisms to prevent unauthorized access. Encryption methods like WEP, WPA, and WPA2 are used for data confidentiality [2]. IEEE 802.11i introduced enhanced security and authentication methods, including IEEE 802.1X (a network access control protocol used to secure Ethernet networks).

H. *Operating Modes*

IEEE 802.11 supports two operating modes: Infrastructure operating mode and Independent operating [2]. Infrastructure mode requires communication through an Access Point, while in Independent mode STAs can communicate directly.

I. *Quality of Service (QoS)*

IEEE 802.11e introduced QoS enhancements to address issues related to MAC techniques in earlier extensions [2]. Two new MAC techniques, HCF(designed for time-sensitive applications) and EDCF(contention windows that prioritize different types of traffic), were introduced to enhance QoS support. Block Acknowledgement and Direct Link Protocol (DLP) were also introduced to improve QoS. Direct Link protocol establishes a direct connection between two devices over a point-to-point link, thereby facilitating data transfer and communication without the need for complex network infrastructure. On the other hand, block acknowledgement acknowledges multiple data frames with a single response. Both these advancements collectively improved efficiency.

J. Contention-Based Protocol (CBP)

IEEE 802.11y introduced contention-based protocols, including ”listen before talk.” This allowed multiple users to share the same radio frequency spectrum without pre-coordination [2].

Extended Channel Switch Announcement (ECSA):

ECSA is used to notify stations about channel changes. This allows for the selection of interference-free channels [2].

K. Dependent Station Enablement (DSE)

DSE is a system that enables an operator to grant or revoke permission for license-exempt devices to use licensed radio spectrum [2].

L. Mobility

IEEE 802.11 initially failed to provide solutions for roaming users, but later standards have addressed smooth transitions between LAN networks for mobile users [2].

III. Different Variants of 802.11

The 802.11 protocol has evolved through various standards, including 802.11a, 802.11b, 802.11g, 802.11ac, and the upcoming 802.11ax:

A. 802.11a

802.11a was first introduced in 1999. It operates in the 5 GHz frequency range and offers data rates up to 54 Mbps [2]. It employed Orthogonal Frequency Division Multiplexing (OFDM) and was one of the first high-speed Wi-Fi standards.

B. 802.11b

This protocol was introduced around the same time as 802.11a. 802.11b operates in the 2.4 GHz band and provides data rates up to 11 Mbps [2]. It utilized Direct Sequence Spread Spectrum (DSSS) modulation.

C. 802.11g

Introduced in 2003, 802.11g improved upon 802.11b by offering higher data rates (up to 54 Mbps) in the 2.4 GHz band [2]. It used OFDM modulation, similar to 802.11a.

D. IEEE 802.11c

This standard covers bridge operation, allowing devices to link two LANs with similar MAC protocols [2]. It works similarly to an IP router but focuses on the MAC layer for efficient connections.

E. IEEE 802.11d

This update resolves regulatory disparities across countries by expanding support for the 5MHz frequency range to North America, Europe, and Japan. To conform with regional regulations, it includes the ”country information element” in beacons and answers [2].

F. IEEE 802.11e

First deployed in 2005, this standard enhances QoS for WLAN applications. It implements time-scheduled and polled communication, boosts channel resiliency, and prioritises traffic for applications such as IP telephony and video streaming [2].

G. IEEE 802.11f

This standard aims to make wireless access point communication between systems from different suppliers easier, allowing for smooth device roaming [2]. This protocol was, however, removed later.

H. IEEE 802.11h

Introduced mechanisms like Dynamic Frequency Selection (DFS) and Transmit Power Control (TPC) to address coexistence with satellite and radar signals in the 5 GHz band [2].

I. IEEE 802.11i

In order to address security concerns, this standard replaces the insecure WEP (Wired Equivalent Privacy) protocol with more secure alternatives such as WPA (Wi-Fi Protected Access) and WPA2 [2]. It also improved the MAC layer's encryption and authentication procedures.

J. IEEE 802.11j

This standard enables WLAN operation in the 4.9 to 5 GHz band to comply with Japanese radio operation rules [2].

K.

IEEE 802.11k For radio resource management, IEEE 802.11k improves roaming decisions, collects channel information, and enhances access point efficiency [2].

L. IEEE 802.11n

It was released in 2009 and focuses on enhancing MAC layer throughput. It makes use of technologies such as MIMO (Multiple-Input, Multiple-Output) and new modulation techniques to boost data rates and efficiency, allowing for greater throughput [2].

M. IEEE 802.11p

Developed for vehicular environments, IEEE 802.11p enables Intelligent Transportation Systems (ITS) applications [2]. It facilitates data exchange between vehicles and roadside infrastructure, enhancing communication for safety and traffic management.

N. IEEE 802.11r

This standard provides fast Basic Service Set (BSS) transition, enabling secure and rapid handoffs between stations [2]. It reduces the roaming delay, making it suitable for real-time applications.

O. IEEE 802.11s

This standard allows wireless devices to create interconnected mesh networks, while focusing on mesh networking. [2]. It supports both static and ad-hoc topologies, making it useful for various applications and use cases.

P. IEEE 802.11u

Published in 2011, IEEE 802.11u improves internetworking with external non-802.11 networks [2]. It enables network discovery and selection and enhances QoS mapping for seamless and reliable network access.

Q. IEEE 802.11v

This standard, introduced in 2011, enables client configuration while connected to the network [2]. It simplifies the process of managing and configuring wireless clients during their network connection.

R. IEEE 802.11w

Published in 2009, IEEE 802.11w enhances security by protecting management frames [2]. It ensures the authenticity of data origin, data integrity, and protection against replay attacks.

S. IEEE 802.11z

This standard, from 2010, extends support for Direct Link Setup (DLS) [2]. It allows two stations to communicate directly without requiring an access point, providing power-saving capabilities.

T. IEEE 802.11aa

Focusing on audio-video streaming, IEEE 802.11aa specifies enhancements to the MAC layer for robust AV streaming [2], ensuring reliable performance and coexistence with other network traffic.

U. 802.11ac

This standard, introduced in 2013, added 80 MHz, 160 MHz, and non-contiguous 160 MHz channel bandwidths, introduced multi-user capabilities, increased modulation schemes, and simplified features from 802.11n. Apart from this, To prevent issues related to interference within the same frequency band and to streamline protocol design, 802.11ac specifies the use of exclusively non-overlapping channels. Figure 2 demonstrates how this is done.

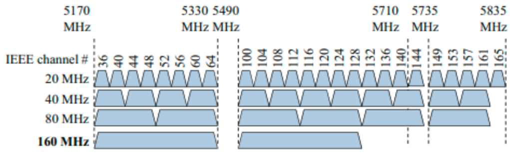

Figure 2. 802.11ac Channelization [1]

V. 802.11ax

802.11ax is in the early stages of development and aims to address coverage, interference, and efficiency issues in Wi-Fi networks. It introduces technologies like simultaneous transmit/receive (STR), downlink and uplink OFDMA, uplink multi-user MIMO, and dynamic clear channel assessment (CCA) [1].

IV. 802.11 Evolution

Figure 3 summarises the advancement in 802.11 so far. However, eveolution of Wi-Fi is still in progress and future seems quite promising.

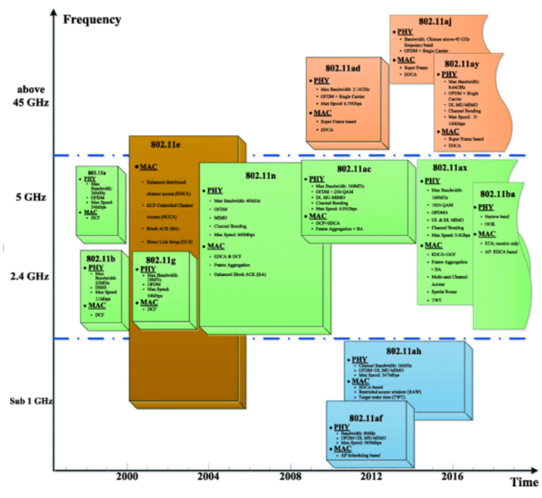

Figure 3. Evolution of IEEE 802.11 [3]

Wi-Fi 6E, has recently emerged following the Federal Communication Commission's decision in April 2020 to open the 6 GHz band for unlicensed uses in the United States. This extension of the frequency spectrum integrated seamlessly with WiFi 6 (802.11ax), retaining all of its existing capabilities. WiFi 6E's wider communication channel reduces interference compared to WiFi 6 and maintains backward compatibility with previous WiFi generations [4]. As more countries adopt the 6 GHz standard for unlicensed applications, WiFi 6E is poised to expand into new markets.

Anticipated for a 2024 release, the IEEE 802.11be Standard, often referred to as WiFi 7, represents the next-generation successor to the current WiFi 6/6E standard. It operates within the 6 GHz band and promises significantly enhanced raw data rates, reaching up to 46.1 Gbps [4]. WiFi 7 introduces advanced features like improved multi-access point coordination, enabling active access points to request idle ones to reduce their output power, minimizing interference from unused devices. Additionally, WiFi 7 implements joint transmission technology, allowing two or more access points to collaborate in providing service to a single device when feasible. This standard employs 360 MHz wide channels, 4096-QAM modulation order, and 16 spatial streams, making it an exciting development in the world of WiFi. Future articles from the Next-Gen Wi-Fi Applications and Solutions Series will delve deeper into the technologies behind Wi-Fi 6/6E and explore the direction of innovation in this field.

V. Conclusion

In conclusion, enhancing network security at the data link layer in the OSI model is crucial to protect against a variety of vulnerabilities and attacks. By implementing the security measures discussed in this paper, network administrators can significantly improve the overall security of their networks at the data link layer.

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