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# Developments in WLAN WiFi Standards, Security and Optimization

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***Abstract:*** ***Wi-Fi has transformed the way people connect and communicate by replacing wired networks with fast, convenient wireless access. Introduced in the late 1990s, it quickly became a key part of everyday life, powering laptops, smartphones, and smart devices. Over the years, Wi-Fi standards have continued to evolve — from basic wireless connections to high-speed, multi-device networks like Wi-Fi 6 and the emerging Wi-Fi 7. These improvements have solved many earlier issues such as limited mobility and slow data transfer. However, Wi-Fi still faces challenges like signal loss through walls, interference from other devices, and reduced performance over distance. This study highlights how Wi-Fi technology has advanced, the problems it helped overcome, and the limitations that remain in creating truly seamless wireless communication. (Charfi, et.al)***
***Keywords: Wi-Fi, RF Signals, Signal-to-Noise Ratio (SNR).***

## I. INTRODUCTION

Dr. John O'Sullivan and his team at CSIRO (Commonwealth Scientific and Industrial Research Organization, Australia) invented wifi (wireless fidelity) technology which radio waves (A type of electromagnetic wave) to transmit data between devices. Wi-Fi (IEEE 802.11 standard) was developed in 1997 and became commercially available around 1999. When Wi-Fi was introduced in the late 1990s, laptops were already available but were bulky and not very portable by today's standards. Most laptops relied on Ethernet cables to connect to networks, which limited mobility and made networking cumbersome. To go wireless, users needed special Wi-Fi cards. Mobile phones existed at the time, but they were primarily used for calls and text messages and did not have Wi-Fi or internet capabilities. The first laptops with built-in Wi-Fi appeared around 1999–2000, and Wi-Fi-enabled phones started emerging a few years later in the early 2000s, solving the limitations of wired connections and paving the way for the wireless, connected world we enjoy today. (Jakobs et al.)

Wireless communication has become a vital part of everyday life, allowing people to stay connected anytime and anywhere. Among the many wireless technologies, Wi-Fi stands out as one of the most common and convenient ways to access the internet. Whether at home, in offices, or in public areas, Wi-Fi plays a major role in supporting modern communication and data transfer. As technology evolves, understanding how Wi-Fi signals behave in real-world environments has become increasingly important for improving performance and reliability.

Wi-Fi systems use radio frequency (RF) signals, which are electromagnetic waves that carry data through the air. However, these signals can be affected by many environmental factors. They may reflect off walls, bend around corners, or get absorbed by obstacles like furniture and building materials. Other factors such as the distance between devices, surrounding interference, and the number of connected users can also weaken the signal and reduce connection quality.

Wi-Fi operates mainly in two frequency bands — 2.4 GHz and 5 GHz — both of which are part of the unlicensed Industrial, Scientific, and Medical (ISM) bands. Because these bands are open for public use, many devices such as Bluetooth accessories, microwaves, and nearby routers share them, often leading to interference. The transmission power of Wi-Fi equipment usually ranges from 100 to 200 mW, though this may vary by region. To minimize interference, modern routers automatically choose the most suitable channel or frequency band.(Korowajczuk et.al,2011)

Each Wi-Fi frequency has its own characteristics. The 2.4 GHz band offers greater range and better wall penetration, but it provides lower data rates. In contrast, the 5 GHz band supports much faster speeds but has a shorter coverage area. Depending on the Wi-Fi standard (like IEEE 802.11b/g/n/ac), the 2.4 GHz band can deliver speeds up to 450–600 Mbps, while the 5 GHz band can reach up to 1300 Mbps under ideal conditions.

Wi-Fi performance is often evaluated using metrics such as throughput, latency, bandwidth, and packet loss. Another key measure is the Received Signal Strength Indicator (RSSI), which shows how strong the signal is between a device and its router. A weak RSSI usually indicates high signal loss, while a high Signal- to-Noise Ratio (SNR) suggests a stable and clear connection. (Kalhans et.al,2020)

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A major challenge for indoor Wi-Fi networks is penetration loss — the reduction of signal strength when radio waves pass through materials like walls, floors, and glass. This happens because part of the signal gets absorbed or reflected by these materials, depending on their composition and thickness.

This study aims to analyze how environmental and structural factors influence Wi-Fi performance in indoor settings. It focuses on identifying how distance, interference, and different construction materials affect signal strength, attenuation, and the overall quality of wireless communication. (Korowajczuk, 2011; Lindroos et al., 2021)

*A. Recent Advances / Key Developments*

1) Over the past two decades, Wireless Local Area Network (WLAN) technology, standardized by the IEEE 802.11 family, has evolved rapidly to meet growing demands for speed, capacity, and security.
2) The early standards such as IEEE 802.11b (1999) and 802.11g (2003) laid the foundation for wireless networking, offering data rates up to 54 Mbps in the 2.4 GHz band.
3) The introduction of IEEE 802.11n (2009) was a major milestone, bringing MIMO (Multiple Input Multiple Output) technology and support for both 2.4 GHz and 5 GHz bands, significantly improving speed (up to 600 Mbps) and range.
4) Subsequent developments like IEEE 802.11ac (Wi-Fi 5, released in 2013) introduced beamforming, channel bonding, and MU-MIMO, enabling multi-gigabit speeds over the 5 GHz band.
5) The latest generations — Wi-Fi 6 (IEEE 802.11ax) and Wi-Fi 7 (IEEE 802.11be) — emphasize OFDMA (Orthogonal Frequency Division Multiple Access), 1024-QAM and 4096-QAM modulation, and multi-user scheduling for enhanced performance in high-density environments.(Afaqui et al. ; Bellalta et al., 2021)
6) These improvements have reduced latency, increased spectrum efficiency, and supported emerging applications like IoT, AR/VR, and smart home automation.
7) In parallel, Wi-Fi security protocols have evolved from the vulnerable WEP to more secure standards such as WPA2 and WPA3, incorporating AES encryption, individualized data encryption, and stronger authentication mechanisms to counter modern cyber threats.(Charfi et al, 2025 ; Halbouni et al, 2023)
8) The integration of Wi-Fi sensing capabilities (IEEE 802.11bf), expected to complement future WLAN standards, enables devices to use Wi-Fi signals for motion detection, gesture recognition, and environmental sensing — expanding Wi-Fi beyond communication into smart surveillance, health monitoring, and indoor positioning applications.
9) Recent advancements also include improved power-efficient mechanisms in modern Wi-Fi standards, enabling longer battery life for IoT and mobile devices through optimized sleep cycles and adaptive power management.

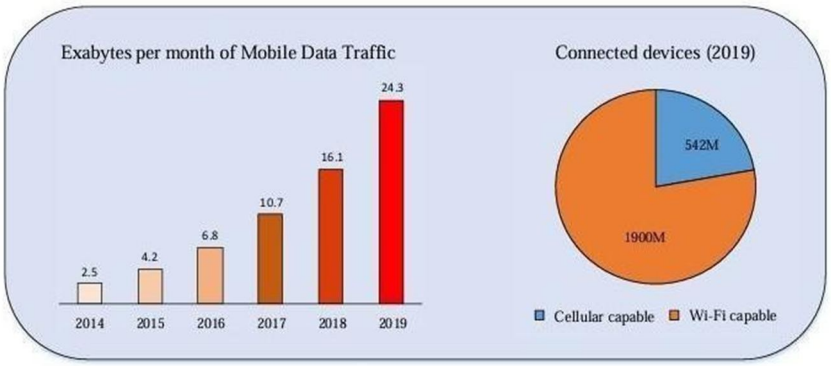



Figure 1: Global Growth of Mobile Data Traffic and Wi-Fi Connectivity (2014–2019) [59]

*B. Comparative Analysis of Approaches*

1) Each Wi-Fi generation has introduced different strategies to enhance throughput, reliability, and efficiency:
2) 802.11n focused on spatial multiplexing (MIMO) and dual-band operation for balanced performance.
3) 802.11ac prioritized high-speed data transmission using beam forming and wide 160 MHz channels in the 5 GHz band.
4) 802.11ax (Wi-Fi 6) introduced OFDMA and MU-MIMO uplink/downlink to improve multi-user access and reduce latency in congested networks.
5) 802.11be (Wi-Fi 7) builds on these principles with enhanced channel bonding (up to 320 MHz) and multi-link operation,

providing theoretical speeds beyond 40 Gbps.(Perahia E,et al., 2013)

6) In terms of security, early approaches like WEP were easily compromised due to weak key management. WPA2 addressed many of these vulnerabilities through AES encryption, while WPA3 now provides forward secrecy and resistance to dictionary attacks, improving overall network trustworthiness. (Gast, 2005; Halbouni, et al., 2023).)
7) Optimization methods can be broadly categorized into two domains:
8) Hardware-based optimization, involving enhanced antenna arrays, tri-band routers, and improved RF components.
9) Software-based optimization, focusing on intelligent algorithms for dynamic channel selection, load balancing, band steering, and QoS (Quality of Service) management.
10) While newer standards have improved performance, trade-offs still exist between speed, coverage, and backward compatibility with older devices.(Bellalta et al., 2021; Charfi et al., 2025).
11) Energy efficiency has become a key differentiating factor across Wi-Fi standards, with recent generations (such as Wi-Fi 6/6E and Wi-Fi 7) incorporating features like Target Wake Time (TWT) and adaptive power management, reducing energy consumption for IoT devices and extending battery life without compromising network performance.

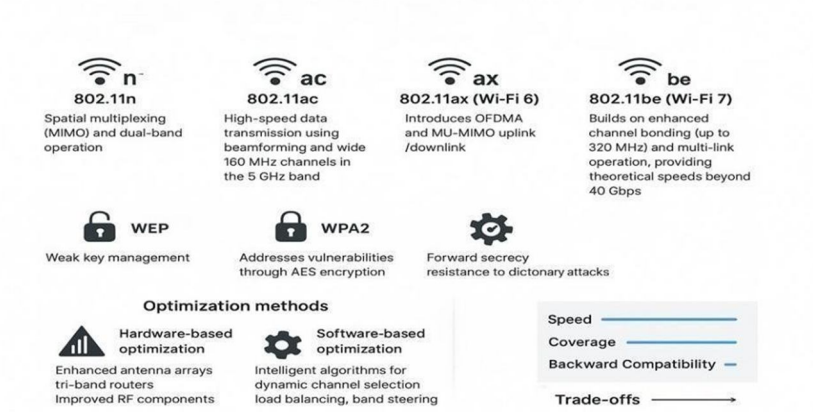


Figure 2: Comparative Analysis of Approaches(2023–2025) [36]

*C. Current Challenges / Limitations*

1) Despite significant advancements, modern Wi-Fi systems still face multiple technical and operational challenges.
2) Signal interference remains a major issue, especially in dense environments where multiple routers, Bluetooth devices, and microwaves operate on overlapping frequencies.
3) Penetration loss caused by building materials like concrete, metal, and glass continues to limit indoor coverage and signal strength.
4) The need for higher data rates also increases power consumption, posing challenges for energy-efficient design, especially in IoT and mobile applications.
5) Although WPA3 has strengthened network security, emerging threats such as side-channel attacks and configuration vulnerabilities still pose risks.
6) Network congestion in public spaces and shared networks continues to reduce performance despite advances in MU-MIMO and OFDMA technologies. (Mozaffariahrar, et al.,2022 ; Bellalta, et al.2021)
7) Additionally, performance inconsistencies caused by differences in router firmware, device capabilities, and network layout make real-world optimization difficult.
8) Current research highlights a gap in the integration of AI-driven network management, adaptive power control, and self-healing wireless systems that can automatically respond to environmental and traffic changes.
9) Future development of Wi-Fi standards should prioritize smart optimization, seamless interoperability with 5G, and sustainable power efficiency to achieve reliable and high-performance wireless connectivity.(Ali et al., 2023; Bellalta et al., 2021; Charfi et al., 2025).
10) The increasing use of higher-frequency bands (such as 6 GHz in Wi-Fi 6E and 7) introduces new limitations, as these signals suffer from reduced range and lower obstacle penetration, requiring more access points and increasing deployment cost for consistent coverage.
11) Compatibility challenges persist as heterogeneous device ecosystems—with varying support for legacy and latest Wi-Fi

standards—lead to sub-optimal performance, forcing networks to operate in mixed-mode and limiting the full potential of advanced features like multi-link operation and high-order modulation.

12) Rising user density and bandwidth-intensive applications like 4K/8K streaming and AR/VR continue to strain Wi-Fi networks, creating challenges in maintaining consistent Quality of Service (QoS) under peak loads.

## II. WLAN ARCHITECTURE

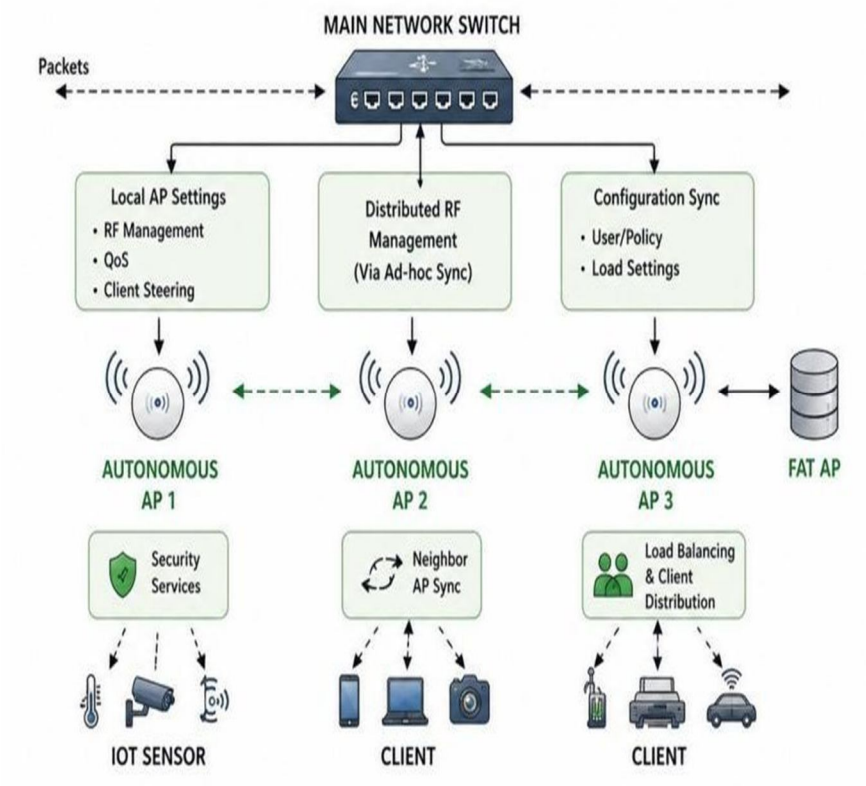



Figure 3: Architecture of WLAN [7]

### A. *Components of Wireless LAN Architecture (as per IEEE Standards)*

1) A Wireless Local Area Network (WLAN) is structured according to IEEE standards, consisting of several essential components that enable efficient wireless communication.
2) Stations (STAs): These are the end devices, such as laptops, smartphones, and access points, equipped with wireless network interface controllers (NICs). They are responsible for transmitting and receiving data over the wireless medium.
3) Basic Service Set (BSS): The BSS represents the core unit of a WLAN. It includes a group of stations that communicate with each other at the physical layer within a specific coverage area, typically through an access point.
4) Extended Service Set (ESS): When multiple BSS units are interconnected through access points, they form an ESS. This structure allows seamless connectivity and user mobility across larger areas while maintaining continuous network access.
5) Distribution System (DS): The DS functions as the central backbone of the WLAN. It interconnects multiple BSSs and ESSs, managing data transfer and ensuring smooth communication between different parts of the wireless network.
6) Access Point (AP): The access point acts as the central transmitter and receiver within a BSS, bridging wireless clients to the wired network and managing functions such as authentication, association, and traffic coordination.
7) Wireless Medium (WM): The shared radio frequency environment through which all stations communicate, serving as the fundamental transmission medium defined by IEEE 802.11 for data exchange over the air (IEEE, 2007).

*B. Comparison of "Evolution of Wi-Fi: Problems Solved, Key Improvements, and Limitations"*

Tble 1: Evolution of WiFi, problems and challenges

| Wi-Fi Versi on / Aspec t | IEEE Stand ard & Year | Main Problems Solved | Key Improveme nts | Limitations / Challenges |
|---|---|---|---|---|
| Befor e Wi-Fi | — | Devices were connected with cables; limited mobility; difficult setup; no wireless sharing. | — | No wireless access or portability. |
| Wi-Fi 1 (802.1 1b) | 1999 | Introduced wireless networking, reducing the need for cables. | 11 Mbps speed, 2.4 GHz frequency for wide range. | Slow speed, interference from microwaves and Bluetooth. |
| Wi-Fi 2 (802.1 1a) | 1999 | Provided faster wireless data transfer. | 54 Mbps, used 5 GHz bandto reduce interference. | Shorter range, expensive, limited device support. |
| Wi-Fi 3 (802.1 1g) | 2003 | Combined strengths of a & b standards. | 54 Mbps, backward compatible, better stability. | Still used 2.4 GHz (crowded band), interference issues. |
| Wi-Fi 4 (802.1 1n) | 2009 | Improved indoor coverage and speed. | Dual-band (2.4 &5 GHz), MIMO technology, up to 600 Mbps. | Real-world speed lower; performance dropswith distance. |
| Wi-Fi 5 (802.1 1ac) | 2013 | Enhanced performance for streaming and gaming. | 1.3 Gbps, stable 5 GHz connection, MU-MIMO support. | Short range; works best with modern devices only. |
| Wi-Fi 6 (802.1 1ax) | 2019 | Solved congestion in dense areas; supported many devices. | Up to 9.6 Gbps; efficient data sharing; OFDMA & MU-MIMO. | Still affected by walls/interfer ence; expensive hardware. |
| Wi-Fi 6E | 2021 | Reduced network congestion further with new band. | Uses 6 GHz band; faster and more reliable in open areas. | Shorter range; limited device compatibility. |
| Wi-Fi 7 (802.1 1be) | 2024–25 | Aims to remove latency and bandwidth limits. | Extremely fast (up to 46 Gbps), supports multi-band use. | Very costly; still being deployed and tested. |

## III. CONCLUSION

In conclusion, Wireless Local Area Networks (WLANs) have evolved into one of the most essential forms of communication technology, offering high flexibility, scalability, and convenience without the need for complex physical cabling. Through continuous advancements in Wi-Fi standards, such as IEEE 802.11n, 802.11ac, and 802.11ax, modern WLANs have achieved faster data transmission, lower latency, and improved network efficiency. These developments have made Wi-Fi the backbone of smart homes, enterprises, and public connectivity systems.

However, despite its versatility, WLANs still face certain technical and security challenges. The open nature of wireless communication exposes networks to risks like unauthorized access, data interception, and interference from external devices. Therefore, strong security mechanisms such as WPA3 encryption, network segmentation, and robust authentication protocols are crucial to safeguard sensitive information and maintain data integrity.

Recent trends in optimization techniques—including dynamic channel selection, MIMO beamforming, and AI-driven interference management—have further enhanced network stability and performance. Yet, issues such as penetration loss, environmental interference, and energy efficiency remain active areas of research.

Overall, the continued development of Wi-Fi standards, improved security protocols, and optimization technologies promises to deliver faster, smarter, and more secure wireless communication systems in the future. WLANs will remain a critical enabler for the connected world, supporting the growing ecosystem of IoT, edge computing, and next-generation digital applications.

## IV. FUTURE PERSPECTIVES AND OPEN CHALLENGES

### *A. Optimization in Dense Network Environments*

As the number of wireless devices keeps growing, Wi-Fi networks often struggle with congestion, especially in busy areas like offices, universities, and smart cities. Future research aims to make Wi-Fi smarter by improving how it handles channel allocation, data traffic, and signal interference, ensuring stable performance even in crowded spaces.

### *B. Compatibility Between Old and New Devices*

Modern Wi-Fi standards, such as Wi-Fi 6, Wi-Fi 7, and the upcoming Wi-Fi 8, need to work smoothly with older devices still in use. Researchers are developing adaptive systems that can automatically balance performance between different device generations by adjusting key parameters like signal thresholds and data frame settings.

### *C. Multi-Access Point (Multi-AP) Coordination*

To extend coverage and improve reliability, future Wi-Fi networks will use multiple access points that work together intelligently. This coordination will help eliminate weak zones, improve data transfer rates, and ensure smooth connectivity as users move between different network areas.

### *D. Low Latency and Fast Handoff*

For real-time applications such as online gaming, virtual reality, and remote medical monitoring, even small delays can be disruptive. Future Wi-Fi versions will focus on reducing latency and improving how quickly devices switch from one access point to another without losing connection.

### *E. Artificial Intelligence and Machine Learning Integration*

Artificial Intelligence (AI) and Machine Learning (ML) are becoming key tools in wireless communication. Future Wi-Fi systems will use AI to predict network congestion, optimize bandwidth automatically, and adjust signal strength based on user activity—making networks faster and more efficient without human intervention.

### *F. Use of Higher Frequency Bands (6 GHz and Beyond)*

Newer Wi-Fi generations are expanding into 6 GHz and even higher frequency bands, allowing for ultra-fast data transmission. However, these higher frequencies have shorter ranges and struggle to penetrate walls. Future developments will rely on advanced techniques like beamforming and signal reflection to overcome these physical limitations.

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### G. *Energy Efficiency and Green Networking*

With billions of connected devices operating worldwide, reducing power use has become a major goal. Researchers are focusing on energy-saving algorithms, low-power transmission methods, and smart sleep modes that help devices conserve energy while maintaining strong network performance.

### H. *Ultra-High Reliability and Quality of Service (QoS)*

Wi-Fi 8 introduces the concept of Ultra-High Reliability (UHR), designed for critical applications such as industrial automation, robotics, and smart manufacturing. Achieving consistent quality of service, even under fluctuating network conditions, is one of the biggest technical challenges still being worked on.

### I. *Security and Privacy Improvements*

As Wi-Fi becomes more essential to daily life, protecting user data is more important than ever. Future networks will include stronger encryption, AI-based threat detection, and improved authentication systems to prevent hacking and unauthorized access.

### J. *Support for IoT and Smart Infrastructure*

The Internet of Things (IoT) relies heavily on Wi-Fi for communication between devices. Future networks must handle massive connections efficiently while using minimal power. Integration with 5G networks and edge computing will help support real-time communication for smart homes, healthcare, and cities.

### K. *Better Mobility and Roaming Performance*

Modern users move constantly—from one building or network to another—so Wi-Fi systems must offer seamless mobility. Future improvements will focus on context-aware roaming, allowing devices to switch between access points smoothly and automatically without affecting the connection quality.

### L. *Dynamic Spectrum Sharing and Management*

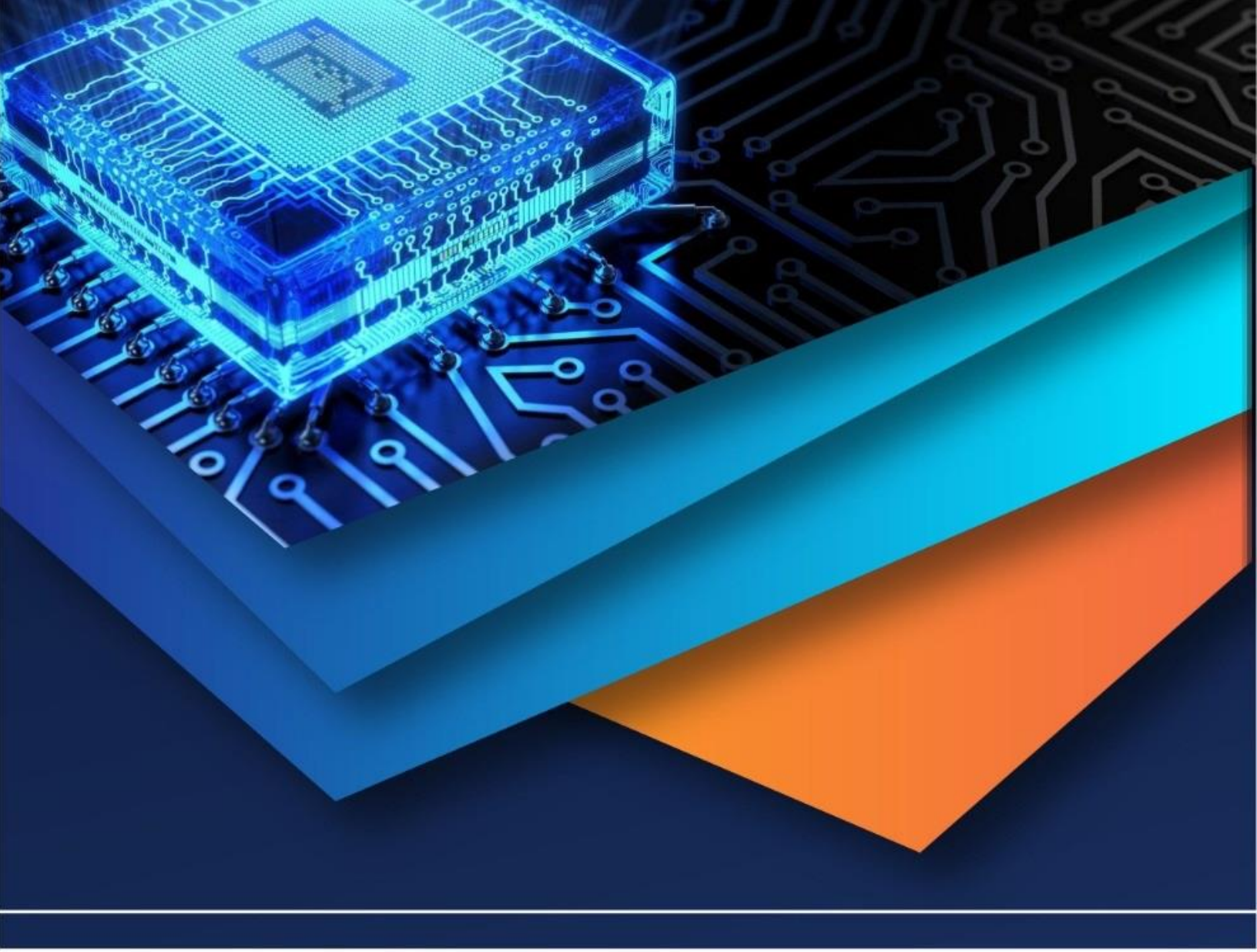
The growing demand for bandwidth makes efficient spectrum use critical. Future Wi-Fi systems will use dynamic spectrum sharing, where available frequencies are intelligently divided among users and devices to reduce interference and maximize data throughput. (Ali et al., 2023; Charfi, et al., 2025; Mozaffariahrar, et al., 2022; Verma, et al., 2023)

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