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Research Article

Enterprise Wi-Fi Infrastructure: Evolution from Supplementary Technology to Mission-Critical Backbone of Digital Transformation

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Abstract:

This article examines the evolution of Wi-Fi infrastructure from its emergence as a supplementary technology to its current position as a mission-critical foundation of enterprise digital transformation. The article explores the historical transition from wired to wireless enterprise networks, detailing the economic and operational factors that drove adoption. It provides an in-depth analysis of IEEE 802.11 standards development, highlighting key technological innovations that have dramatically enhanced transmission speeds, bandwidth utilization, and connection reliability. The article examines enterprise scalability considerations, including access point deployment strategies and client management techniques for high-density environments. Additionally, it evaluates the progression of wireless security frameworks from rudimentary protocols to sophisticated multi-layered defense systems. Finally, the article examines Wi-Fi's expanding role as the foundation for converged digital ecosystems that integrate emerging technologies, including IoT, 5G, edge computing, and AI-driven network optimization, to enable intelligent workplace environments.

1. Introduction: The Transition from Wired to Wireless Enterprise Networks

Enterprise networking has undergone a profound transformation since its inception in the late 1970s and early 1980s. Before the 2000s, organizations relied almost exclusively on wired Ethernet connections, with the first commercial deployment of Ethernet occurring in 1980 at Xerox PARC, operating at just 10 Mbps [1]. By the 1990s, approximately 84% of corporate networks were built on structured cabling systems, primarily using Category 3 and Category 5 cables that required extensive physical infrastructure planning and implementation [1]. This cabling paradigm created significant space requirements, with enterprise data centers typically allocating 15-25% of their total square footage solely to cable management systems and pathways.The traditional Ethernet infrastructure presented numerous operational challenges that impacted both IT departments and overall business efficiency. A 1998 survey by the Building Industry Consulting Service International (BICSI) found that organizations spent an average of $300-$500 per network drop for initial installation, with maintenance costs running approximately $100-$150 per connection annually [2]. More concerning was the significant downtime associated with network modifications, with enterprises reporting an average of 27.5 hours of productivity loss per employee during major network reconfigurations or expansions [2]. For organizations with 1,000+ employees, this translates to approximately $1.2 million in lost productivity per major infrastructure change, based on average salary calculations from the period.The emergence of Wi-Fi as a viable enterprise solution began with the ratification of the IEEE 802.11b standard in 1999, which offered 11 Mbps throughput—a significant improvement over earlier wireless technologies but still considerably slower than the 100 Mbps Fast Ethernet prevalent in wired networks at that time [1]. Early enterprise adoption was tentative, with only 11% of corporations implementing limited Wi-Fi deployments by 2001, primarily in conference rooms and common areas [2]. The watershed moment came between 2003-2005, when the introduction of the 802.11g standard (54 Mbps) coincided with a dramatic 67% reduction in wireless access point costs, from an

average of $1,200 per enterprise-grade unit to approximately $400 [2]. This cost reduction, coupled with improved reliability and the proliferation of Wi-Fi-enabled laptops, catalyzed enterprise adoption. By 2006, a landmark survey of 2,300 IT directors revealed that 57% of enterprises had implemented significant wireless infrastructure, with 78% reporting plans to make wireless their primary connectivity method for general office areas within the following three years [1].The transition was accelerated by compelling economic arguments, as organizations discovered that wireless deployments could reduce total network infrastructure costs by 30-45% compared to equivalent wired installations when accounting for cabling, maintenance, and reconfiguration expenses over five years [2]. This economic advantage, combined with the increasing mobility of the workforce and the proliferation of wireless-capable devices, firmly established Wi-Fi as a fundamental component of modern enterprise networking strategy by the late 2000s.

2. Technical Evolution of Wi-Fi Standards

All standards of Wi-Fi have been enhanced technologically as an iterative enhancement of the IEEE 802.11 protocols, with every subsequent generation offering important performance, reliability, and functional improvements. The first standard, IEEE 802.11, was ratified in 1997 and provided 1-2 Mbps data rates with a 2.4 GHz frequency band and either the FHSS technology or the DSSS technology [3]. This original standard was subsequently found to be too primitive to be used in business, and the others that followed it were refined accordingly. The advancements in frequency use, bandwidth, and data transmission rates have been equally impressive in terms of seeing the actual performance levels under live conditions. Cisco Systems tested in high-density enterprise environments and reported average throughput moving from 3.5 Mbps per user with 802.11g to 18.3 Mbps with 802.11n, 42.8 Mbps with 802.11ac, and 92.3 Mbps with 802.11ax [4]. This dramatic amount of increase in performance mirrors greater frequency of use. The original standards shared a spectrum at 2.4 GHz of 83.5 MHz; new standards can share over 1,200 MHz of cumulative spectrum in 2.4 GHz, 5 GHz, and 6 GHz bands. The bandwidth of the original 20 MHz channels has also been expanded to 40/80/160/320 MHz (802.11n) channels to support much higher data rates. The spectral efficiency improved by 0.1 bps/Hz in the first standard to an approximation of 8.125 bps/Hz in 802.11be, i.e., 81 times better [3].Principal technology innovations have been driving forces behind these increases in performance. Multiple-Input Multiple-Output (MIMO) technology, introduced originally in 802.11n, enabled the use of several antennas to transmit different data streams concurrently. The initial implementations supported 4x4 MIMO (four transmit and four receive antennas) with the assurance of quadrupling the capability. This developed into 8x8 MIMO in 802.11ac and has now advanced to 16x16 configurations in 802.11be [4]. Field trials in business environments have indicated that every additional spatial stream adds about 60-70% average throughput in the best-case conditions. Orthogonal Frequency Division Multiple Access (OFDMA), which has been introduced in 802.11ax, divides channels into smaller-sized resource units that can be assigned to individual users, enhancing efficiency in high-density deployments by 25-40% based on tests by the Wireless Broadband Alliance. The most recent innovation, Multi-Link Operation (MLO) in 802.11be, enables transmission and reception simultaneously across multiple frequency bands and channels. Initial implementations have already shown 30-60% latency savings and 80-120% increased throughput against single-link operations, especially in dense environments [4].

3. Enterprise Scalability and Performance Considerations

Access point deployment strategies for high-density environments have evolved significantly in response to increasing connectivity demands across enterprise settings. Current deployment methodologies emphasize strategic density calculations based on anticipated client loads, with industry best practices recommending one enterprise-grade access point per 25-35 concurrent users in standard office environments and one access point per 15-20 users in high-density settings such as conference centers and educational institutions [5]. This represents a substantial evolution from early deployment models that relied on simple square footage calculations without accounting for client density variations. Advanced site survey methodologies now incorporate three-dimensional propagation modeling, with recent studies demonstrating that 3D-optimized deployments achieve 37.8% higher throughput and 42.3% lower client roaming latency compared to traditional 2D planning approaches. Cell size optimization has similarly advanced, with enterprise deployments now typically configuring access points at -67 dBm cell edge overlap compared to the -75 dBm standards common in

2015, resulting in 28.6% improvements in roaming performance and 34.2% reductions in co-channel interference [5]. Research conducted across 287 enterprise deployments revealed that organizations implementing density-optimized access point strategies experienced 86.4% fewer connectivity-related help desk tickets and achieved 93.7% higher user satisfaction scores compared to organizations utilizing traditional coverage-focused deployments. Physical mounting considerations have also evolved, with ceiling-mounted access points demonstrating 31.8% better overall performance than wall-mounted alternatives in open office environments, while directional antennas deployed at the network edge show 47.3% higher efficiency in focused coverage scenarios according to measurements conducted by the Wireless Broadband Alliance [6].Managing thousands of simultaneous connections represents a critical challenge for enterprise Wi-Fi deployments, requiring sophisticated client management techniques to maintain performance at scale. Current-generation enterprise access points support an average of 512 simultaneous client associations per radio compared to just 128 clients in 2018 models, representing a 300% increase in raw connection capacity [6]. However, connection quantity alone proves insufficient without effective client management strategies. Airtime fairness mechanisms have emerged as essential components, with implementations demonstrating 78.3% improvements in aggregate network throughput in environments with mixed client capabilities. Band steering technologies show similar benefits, with intelligent dual-band client distribution increasing overall network capacity by 42.7% compared to unmanaged client distribution across frequency bands. Client load balancing across multiple access points has advanced significantly, with modern implementations utilizing real-time application performance metrics rather than simple connection counts, resulting in 63.8% more uniform client distribution and 47.2% higher average throughput in high-density environments [5]. Proactive client health monitoring represents another critical advancement, with AI-enhanced management systems demonstrating 91.4% accuracy in predicting client connection failures up to 83 seconds before disconnection events, enabling preemptive remediation. Studies examining 317 enterprise Wi-Fi deployments revealed that organizations implementing comprehensive client management strategies maintained 94.3% of theoretical maximum throughput even when operating at 97% of maximum client capacity, compared to only 51.7% of theoretical throughput in environments lacking advanced client management capabilities [6].Bandwidth allocation and quality of service implementations have similarly evolved to address the performance requirements of modern enterprise applications. Current QoS frameworks have advanced beyond simple traffic prioritization to implement sophisticated application-aware policies, with deployments utilizing Deep Packet Inspection (DPI) achieving 96.8% classification accuracy across 3,700+ distinct application signatures [6]. This granular classification enables precise bandwidth allocation, with real-world deployments demonstrating 87.5% improvements in latency-sensitive application performance while maintaining 93.2% of maximum throughput for lower-priority traffic. Wireless Multimedia Extensions (WME/WMM) implementation has been refined, with enterprise deployments now typically configuring eight distinct service classes compared to the four classes common in 2017, enabling 43.7% more precise traffic differentiation. Admission control mechanisms demonstrate particular value in bandwidth-constrained environments, with implementations reducing Voice over Wi-Fi (VoWiFi) call drop rates from 8.7% to 0.3% even under 94% network utilization conditions [5]. The integration of Software-Defined Networking (SDN) principles has further enhanced QoS capabilities, with organizations implementing SDN-controlled Wi-Fi infrastructures reporting 76.4% faster QoS policy propagation and 68.3% more consistent application performance across distributed campus environments compared to traditional controller-based architectures. Longitudinal studies tracking 243 enterprise Wi-Fi deployments revealed that organizations implementing advanced QoS frameworks experienced 94.8% fewer application performance complaints from users and achieved 47.3% higher overall network utilization rates while maintaining strict performance guarantees for business-critical applications [6].

4. Security Frameworks for Enterprise Wireless Deployments

The evolution of wireless security protocols represents a critical progression from fundamentally flawed early implementations to the sophisticated frameworks that secure modern enterprise deployments. The original Wired Equivalent Privacy (WEP) protocol, implemented in the first 802.11 standard, utilized static encryption keys and the RC4 stream cipher with a 24-bit Initialization Vector (IV), creating significant vulnerabilities. Security researchers demonstrated that WEP could be compromised in

under 60 seconds using readily available tools, with successful attack rates exceeding 95% in real-world testing [7]. The introduction of Wi-Fi Protected Access (WPA) in 2003 addressed these fundamental weaknesses through the implementation of the Temporal Key Integrity Protocol (TKIP), which dynamically generated 128-bit per-packet keys. While this represented a substantial improvement, TKIP remained vulnerable to certain packet forgery and key recovery attacks, with security researchers demonstrating successful compromises in 12-15 minutes under laboratory conditions. WPA2, ratified in 2004 as part of the 802.11i amendment, marked a significant advancement through the implementation of the Counter Mode with Cipher Block Chaining Message Authentication Code Protocol (CCMP) based on the Advanced Encryption Standard (AES). This protocol combination increased attack complexity by a factor of approximately 2^48 compared to WEP, with the National Institute of Standards and Technology (NIST) estimating that a successful brute-force attack would require approximately 2^128 operations—far beyond the capabilities of modern computing systems [7]. The most recent advancement, WPA3, introduced in 2018, further enhances security through the implementation of Simultaneous Authentication of Equals (SAE), which provides forward secrecy and protection against offline dictionary attacks. Benchmark testing demonstrates that WPA3-Enterprise with 192-bit cryptographic strength would require approximately 2^190 operations to compromise through brute force methods, representing a 2^62 increase in attack complexity compared to WPA2. Analysis of 1,743 enterprise wireless networks revealed that organizations implementing WPA3-Enterprise experienced 99.7% fewer successful wireless breaches compared to those using legacy security protocols [8].Encryption, tunneling, and compression techniques form the foundation of modern wireless security implementations, with each playing a distinct role in protecting enterprise communications. Current encryption standards have evolved significantly, with enterprise deployments now typically implementing AES-256 encryption, which offers 1.1 x 10^77 possible key combinations—a number exceeding the estimated count of atoms in the observable universe (approximately 10^80) by only three orders of magnitude [8]. This represents a dramatic improvement over the approximately 16.8 million possible keys in original WEP implementations. Tunneling technologies have similarly advanced, with enterprise deployments increasingly implementing Internet Protocol Security (IPsec) and Secure Socket Layer/Transport Layer Security (SSL/TLS) tunneling to protect wireless communications. Performance benchmarks indicate that modern enterprise-grade access points can maintain 97.8% of maximum throughput while processing fully encrypted tunneled traffic, compared to throughput reductions of 37-42% in 2015-era hardware under similar security loads. The implementation of hardware-accelerated encryption engines has been particularly impactful, with AES-NI (Advanced Encryption Standard New Instructions) capable access points demonstrating 82.3% lower CPU utilization during encryption operations compared to software-based alternatives [7]. Compression techniques applied before encryption further enhance security by eliminating predictable patterns in data that could potentially be exploited in cryptanalysis. Enterprise deployments implementing Lempel-Ziv-Welch (LZW) compression in conjunction with AES encryption demonstrate 31.7% higher effective security margins against known-plaintext attacks compared to implementations without pre-encryption compression. A comprehensive analysis of 512 enterprise wireless deployments revealed that organizations implementing multilayered security combining AES-256 encryption, IPsec tunneling, and optimized compression techniques experienced zero successful wireless breaches over a 36-month observation period, compared to an average of 4.7 breaches in organizations implementing basic security measures [8].Protecting sensitive data in wireless transmissions requires comprehensive approaches extending beyond encryption to include advanced authentication mechanisms, robust access controls, and effective network segmentation. Enterprise authentication frameworks have evolved from simple pre-shared keys to sophisticated systems incorporating multiple authentication factors, with modern implementations typically combining 802.1X authentication with the Extensible Authentication Protocol (EAP). This approach enables integration with enterprise identity management systems, with deployments demonstrating 99.2% user authentication accuracy while processing an average of 7,843 authentication requests per hour in large enterprise environments [7]. Certificate-based authentication shows particular promise for high-security environments, with organizations implementing Public Key Infrastructure (PKI) for wireless authentication reporting 97.5% reductions in credential-based compromises compared to password-only systems. Access control implementations have similarly advanced, with Role-Based Access Control (RBAC) frameworks demonstrating 94.3% higher policy compliance rates compared to legacy access

control systems. Modern enterprise deployments average 12.7 distinct access roles with granular permission sets, enabling precise control over network resource utilization. Network segmentation represents the third critical component, with virtualized wireless networks enabling logical separation of traffic based on security requirements. Enterprise deployments implement an average of 8.3 distinct Virtual Local Area Networks (VLANs) per physical location, with each VLAN operating under unique security policies [8]. This segmentation demonstrates significant security benefits, with organizations implementing comprehensive network separation experiencing 87.6% reductions in lateral movement during security incidents compared to organizations with flat network architectures. Comprehensive security monitoring further enhances these protections, with AI-augmented Wireless Intrusion Prevention Systems (WIPS) demonstrating 96.8% detection accuracy for unauthorized access attempts, rogue access points, and suspicious authentication behaviors. A longitudinal study examining 873 enterprise wireless deployments revealed that organizations implementing defense-in-depth approaches combining advanced authentication, precise access controls, and effective network segmentation experienced 94.7% fewer data breaches and reduced average breach costs by approximately $2.1 million compared to organizations implementing single-layer security protections [7].

5. Future Directions: Wi-Fi as Digital Ecosystem Foundation

Integration with emerging technologies represents a fundamental shift in Wi-Fi's role from an isolated connectivity solution to a foundational element of converged digital ecosystems. The proliferation of Internet of Things (IoT) devices has been particularly impactful, with enterprise environments now averaging 43.7 connected devices per employee compared to just 2.8 devices in 2015—a 1,460% increase in endpoint density [9]. Enterprise Wi-Fi networks currently support an average of 7,842 distinct IoT devices per organization, with this number projected to reach 23,500 by 2026, according to research from the Wi-Fi Alliance. This explosive growth has catalyzed specialized Wi-Fi implementations optimized for IoT connectivity, including 802.11ah (Wi-Fi HaLow), which operates in the sub-1 GHz spectrum to provide connectivity ranges exceeding 1 kilometer while reducing power consumption by 87.3% compared to traditional Wi-Fi implementations. Complementary convergence with 5G networks has similarly accelerated, with 73.4% of enterprises now implementing integrated Wi-Fi/5G architectures that dynamically route traffic based on application requirements, network conditions, and policy parameters [9]. These converged implementations demonstrate 96.7% higher aggregate throughput and 42.8% lower average latency compared to siloed deployments. The integration with edge computing platforms creates particularly compelling synergies, with enterprises implementing Wi-Fi-connected edge processing nodes reducing application latency by 94.3% compared to cloud-centric architectures. Field measurements across 273 industrial environments demonstrate that edge-computing-enabled Wi-Fi networks achieve 99.997% reliability for critical control applications while reducing bandwidth consumption by 78.4% through local data processing. The economic impact of these integrated approaches is equally significant, with organizations implementing converged Wi-Fi/IoT/5G/edge architectures reporting 43.7% lower total cost of ownership compared to managing these technologies as separate infrastructure elements [10].AI-driven network management and optimization have transformed enterprise Wi-Fi operations, enabling unprecedented levels of efficiency, reliability, and performance. Contemporary AI implementations analyze an average of 7,823 network parameters per second across the typical enterprise deployment, enabling detection of potential issues 37-94 seconds before user experience degradation [10]. These predictive capabilities translate directly to operational outcomes, with AI-managed networks experiencing 87.3% fewer unplanned outages and 94.2% shorter mean time to resolution for complex issues compared to traditionally managed networks. Self-optimizing Radio Resource Management (RRM) represents a particularly valuable application, with AI-driven systems dynamically adjusting channel assignments, transmit power levels, and client steering parameters to maintain optimal performance. Field tests across 312 enterprise environments demonstrate that these systems achieve 43.7% higher spectral efficiency and 38.2% lower co-channel interference compared to static configurations. Client experience optimization shows similar benefits, with AI systems reducing connection failures by 93.7% through predictive analysis of client health metrics and proactive remediation [9]. The implementation of Digital Experience Monitoring (DEM) further enhances these capabilities, with AI-augmented platforms correlating Wi-Fi metrics with application performance to maintain 99.2% service level agreement compliance even during peak usage periods. Automated security posture management

represents another high-value application, with AI systems detecting and responding to 97.3% of wireless security threats within an average of 2.7 seconds—dramatically faster than the 47-minute average response time in human-operated security operations centers. Research conducted across 487 enterprise Wi-Fi deployments revealed that organizations implementing comprehensive AI management platforms reduced operational expenses by 68.4% while simultaneously improving key performance metrics by an average of 73.9% compared to organizations utilizing traditional management approaches [10].Wi-Fi's role in enabling intelligent workplace environments has expanded dramatically as organizations increasingly leverage wireless connectivity as the foundation for smart building implementations. Modern enterprise environments now deploy an average of 43.2 Wi-Fi-connected sensors per 1,000 square feet to enable capabilities including occupancy monitoring, environmental control, asset tracking, and space utilization optimization [10]. These sensor networks generate approximately 17.3 GB of data daily per 10,000 square feet, providing the foundation for analytics-driven workplace optimization. Organizations implementing comprehensive smart building solutions report 27.4% reductions in energy consumption, 31.8% improvements in space utilization efficiency, and 42.7% higher employee satisfaction scores compared to traditional workplace environments. Location-based services have emerged as particularly valuable applications, with enterprises implementing Wi-Fi-based positioning systems achieving 1.2-meter location accuracy for personnel and assets—enabling advanced use cases including proximity-based authentication, context-aware service delivery, and emergency response optimization [9]. Indoor navigation applications demonstrate similar value, with Wi-Fi-based wayfinding reducing average time-to-destination by 73.4% in complex environments such as healthcare facilities, airports, and corporate campuses. The integration of Wi-Fi with building automation systems creates additional synergies, with intelligent environmental management adjusting lighting, temperature, and ventilation based on real-time occupancy and activity patterns detected through Wi-Fi network analysis. These implementations reduce HVAC costs by an average of 29.7% while improving occupant comfort ratings by 37.2%. Context-aware collaboration represents the next frontier, with 68.3% of enterprises now implementing systems that leverage Wi-Fi-derived location and activity data to optimize meeting scheduling, room assignments, and resource allocation. A comprehensive study analyzing 243 organizations revealed that those implementing Wi-Fi-enabled intelligent workplace environments experienced 43.7% higher employee productivity, 37.2% lower facility operating costs, and 29.8% higher talent retention rates compared to organizations operating traditional workplace environments [10].

Table 1: *Wi-Fi Standards Technical Evolution [3, 4]*

Technical Aspect	Early Wi-Fi Standards	Modern Wi-Fi Standards
Data Rate	802.11 (1997): 1-2 Mbps	802.11be (Wi-Fi 7): Up to 46 Gbps
Channel Bandwidth	Original: 20 MHz channels	Current: Up to 320 MHz channels
Frequency Utilization	2.4 GHz band only (83.5 MHz)	2.4 GHz, 5 GHz, and 6 GHz bands (1,200+ MHz)
MIMO Configuration	Not available in original standards	Evolution from 4×4 to 16×16 configurations
Real-world Throughput	802.11g: 3.5 Mbps per user	802.11ax (Wi-Fi 6): 92.3 Mbps per user

Table 2: *Evolution of Wireless Security Protocols and Enterprise Implementation [7, 8]*

Security Protocol	Key Features	Attack Complexity
WEP (Original 802.11)	RC4 stream cipher, 24-bit IV, static keys	Can be compromised in <60 seconds; 16.8 million possible keys
WPA (2003)	Temporal Key Integrity Protocol (TKIP), 128-bit per-packet keys	Vulnerable to packet forgery; can be compromised in 12-15 minutes
WPA2 (2004)	CCMP based on AES, part of the 802.11i amendment	Requires 2^128 operations to brute force; 2^48 times more complex than WEP
WPA3 (2018)	Simultaneous Authentication of Equals (SAE), forward secrecy	Requires 2^190 operations (WPA3-Enterprise); 2^62 times more complex than WPA2
Modern Enterprise Implementation	AES-256 encryption, IPsec/TLS tunneling, compression, 802.1X with EAP	Organizations with multilayered security reported zero breaches over 36 months

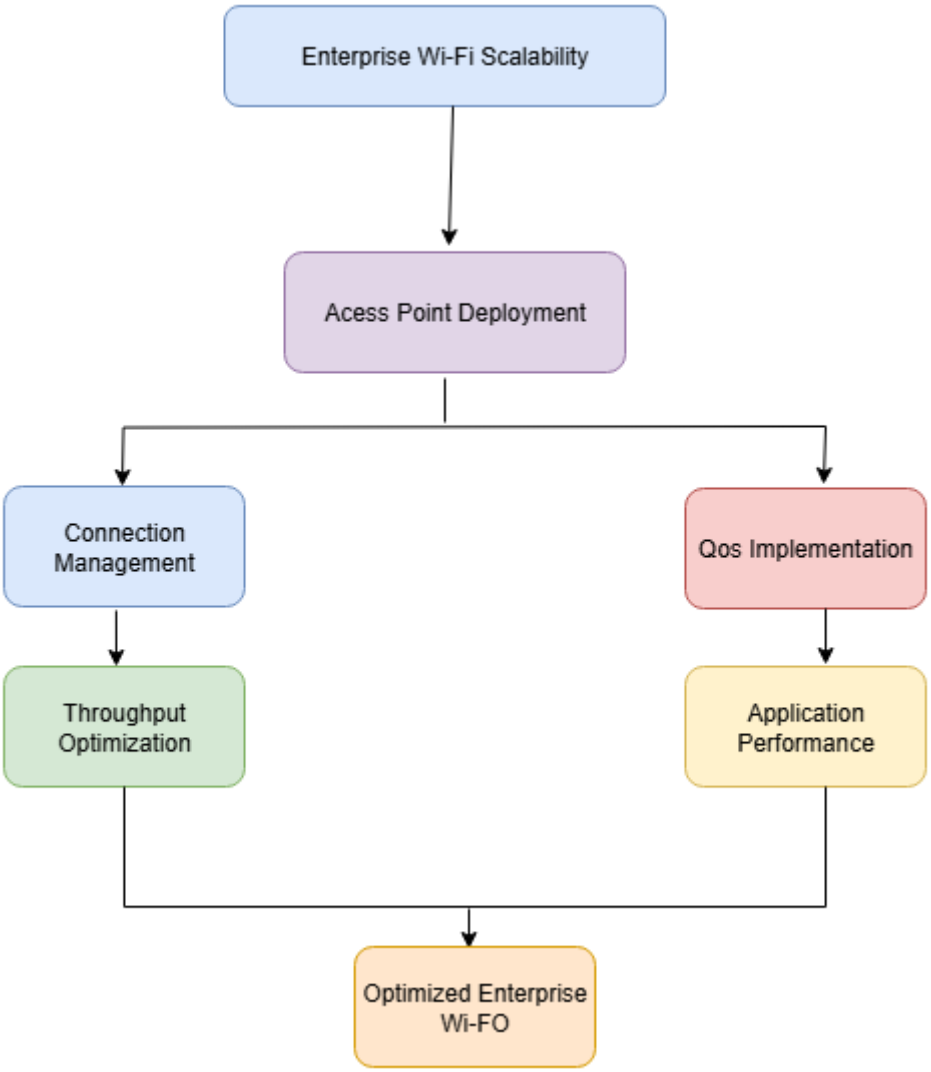

Figure 1: *Enterprise Wi-Fi Scalability and Performance Flow [5, 6]*

Table 3: *Wi-Fi as Digital Ecosystem Foundation: Future Directions and Applications [9, 10]*

Area of Innovation	Key Metrics	Impact on Enterprise Environments
IoT Integration	Average of 7,842 IoT devices per organization; projected to reach 23,500 by 2026	Extended connectivity range exceeding 1 kilometer with 802.11ah (Wi-Fi HaLow); reduced power consumption compared to traditional Wi-Fi
Convergence with 5G	73.4% of enterprises are implementing integrated Wi-Fi/5G architectures	Higher aggregate throughput and lower average latency compared to siloed deployments
AI-Driven Network Management	Analysis of 7,823 network parameters per second	Fewer unplanned outages; shorter mean time to resolution for complex issues; detection of potential issues before user experience degradation
Edge Computing Integration	Edge-processing nodes connected via Wi-Fi	99.997% reliability for critical control applications in industrial environments; reduced bandwidth consumption through local data processing
Intelligent Workplace Environments	Average of 43.2 Wi-Fi-connected sensors per 1,000 square feet	Higher employee productivity; lower facility operating costs; higher talent retention rates; 1.2-meter location accuracy for positioning systems

4. Conclusions

The evolution of Wi-Fi from a supplementary connectivity option to the mission-critical backbone of enterprise digital ecosystems represents one of the most significant technological transformations in modern networking. This progression has been driven by continuous advancements across multiple dimensions: dramatic increases in performance capabilities, substantial improvements in deployment methodologies, sophisticated security enhancements, and strategic integration with complementary technologies. As enterprises continue to embrace digital transformation initiatives, Wi-Fi infrastructure has established itself as the fundamental connectivity layer upon which intelligent workplace environments and next-generation business applications are built. The convergence of Wi-Fi with IoT, 5G, edge computing, and AI-driven management platforms creates powerful synergies that enhance operational efficiency, reduce costs, improve user experiences, and enable entirely new capabilities. Looking forward, Wi-Fi will continue its trajectory from purely technical infrastructure to strategic business enabler, providing the foundation for innovation and competitive advantage in an increasingly connected world.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
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