



# Comparative Performance and Techno-Economic Analysis of Wi-Fi 6 and Private 5G Networks in Industrial and Enterprise Environments

Rahul Bangera  
Ellicott City, MD, USA.

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**Abstract** - The rise of Industry 4.0 has prompted a critical review of wireless connectivity standards, requiring a shift from "best-effort" networking to deterministic, ultra-reliable communication systems. Between 2020 and 2024, two main technologies emerged as contenders for the wireless edge: IEEE 802.11ax, marketed as Wi-Fi 6, and 3GPP Releases 16 and 17, known as Private 5G (P5G) networks. This research paper provides a comprehensive, empirical comparison of these technologies by combining data from academic studies, industry benchmarks, and techno-economic models. The analysis reveals a clear distinction in performance features. While Wi-Fi 6 offers cost-effective solutions for high-density IT environments, measurements show it has unbounded tail latencies reaching up to 264 ms during mobility and packet loss during client roaming. In contrast, Private 5G networks employing scheduled access maintain bounded latencies (typically under 45 ms at the 99.99th percentile) and experience negligible packet loss during handoffs. Moreover, techno-economic models challenge the assumption that Wi-Fi is always cheaper; in large industrial areas (>100,000 sq. ft.), Private 5G can reduce Total Cost of Ownership (TCO) by as much as 53% by lowering infrastructure costs and preventing operational downtime.

**Keywords** - Wi-Fi 6, IEEE 802.11ax, Private 5G, 3GPP Release 16, Industrial IoT (IIoT), Total Cost of Ownership (TCO), URLLC, Target Wake Time (TWT), C-DRX.

## 1. Introduction

The digitalization of industrial processes heavily depends on widespread and reliable data exchange. As companies move from wired Ethernet to wireless solutions to improve the flexibility of assets such as Automated Guided Vehicles (AGVs) and collaborative robots, the limitations of older wireless standards have become clear. This has led to the simultaneous development of two standards: the sixth generation of Wi-Fi (IEEE 802.11ax) and the fifth generation of cellular mobile communications (5G NR) designed for private deployment [1].

### 1.1. The Evolution of Wireless Standards

Historically, Wi-Fi and cellular technologies operated in separate areas: Wi-Fi for unlicensed indoor Local Area Networks (LANs) and cellular for licensed Wide Area Networks (WANs). However, the introduction of IEEE 802.11ax and 3GPP Release 16 has begun to merge these boundaries. Wi-Fi 6 added Orthogonal Frequency-Division Multiple Access (OFDMA) to introduce determinism to a protocol traditionally based on contention. At the same time, regulators have democratized access to cellular spectrum (for example, CBRS in the US), enabling enterprises to deploy Private 5G networks independently [2].

### 1.2. The Determinism Dilemma

The primary concern for enterprise decision-makers is not bandwidth but "determinism." In an office, a 200 ms latency spike is just an annoyance; in a manufacturing plant,

it can cause an emergency stop of a robotic arm [3]. Empirical benchmarks show that the "cost" of a network is increasingly defined by the cost of instability (Operational Expenditure) [3]. This paper examines whether Wi-Fi 6 can support critical workloads or if centralized scheduling of Private 5G is necessary for industrial automation [4].

## 2. Theoretical Framework: Physical Layer and Architecture

To understand the divergence in empirical performance, one must analyze the Physical Layer (PHY) and Medium Access Control (MAC) architectures.

### 2.1. Waveform Numerology and Subcarrier Spacing

Numerology determines resistance to interference and to physical effects such as the Doppler effect.

- Wi-Fi 6 (IEEE 802.11ax): Uses a fixed subcarrier spacing of 78.125 kHz, which is one-fourth of the spacing used in Wi-Fi 5. As a result, the symbol duration increases to 12.8  $\mu$ s [5]. This longer symbol duration enhances efficiency by decreasing the guard interval overhead relative to the payload.
- Private 5G (3GPP NR): Utilizes a scalable numerology defined by  $\Delta f = 2^\mu \times 15$  kHz. In Frequency Range 1 (FR1), typical deployments use 15 kHz or 30 kHz spacing [6].

### 2.2. Modulation and Spectral Efficiency

Wi-Fi 6 aims for maximum throughput with 1024-QAM (Quadrature Amplitude Modulation), encoding 10 bits per symbol [5]. However, this requires a high Signal-to-Noise Ratio (SNR) that is rarely consistent in industrial warehouses. Private 5G usually uses 256-QAM for the downlink, compensating with strong channel coding, such as Polar Codes for control channels and LDPC for data, to keep connections stable at the cell edge [7].

### 2.3. The Fundamental Divergence: MAC Layer Access

- Wi-Fi 6 (Contention): Although OFDMA is used,

access is managed by CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) and "Listen Before Talk" (LBT). This results in probabilistic backoff timers, leading to variable jitter under load [8].

- Private 5G (Scheduling): Operates on a deterministic, scheduled basis. The gNodeB (Base Station) assigns specific Time-Frequency Resource Blocks (RBs) to devices. This prevents contention and ensures the network can guarantee transmission slots for critical sensors regardless of network load [9].

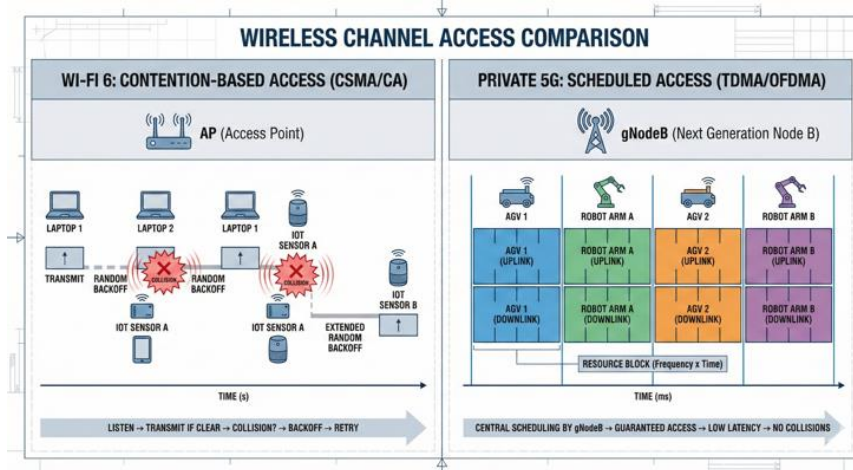


Fig 1: Channel Access Mechanisms Comparison between Wi-Fi 6 and Private 5G

## 3. Empirical Performance Analysis

Recent studies have gone beyond theoretical comparisons to assess real performance in difficult environments.

### 3.1. Latency Distributions

In industrial automation, the "tail" of the latency distribution (e.g., 99.99th percentile) dictates operational speed.

- Median Performance: A study at Aalborg University found that in low-load, stationary scenarios, Wi-Fi 6 achieved lower median latency (~3.7–4.7 ms) than 5G Standalone (~4.8 ms) [10].
- Tail Latency (Reliability): The divergence occurs at the tail. As device count rises, Wi-Fi 6 tail latency increases sharply, reaching 128 ms for large packets. In contrast, 5G SA maintains a bounded tail between 27.6 ms and 34.4 ms [10]. Another study observed Wi-Fi 6 tail latencies reaching 264 ms in mobility scenarios, while 5G remains stable.
- Packet Stability: Research on Network slicing in Private 5G Networks showed that, while Wi-Fi networks experienced significant packet drops under high uplink and downlink loads, 5G systems maintained consistent throughput and very low packet error rates [11].

### 3.2. Mobility and Handover Robustness

- Roaming Mechanism: Wi-Fi roaming is initiated by the client; the device determines when to switch Access Points (APs), often staying connected to a weak signal for too long (a "sticky client"). 5G roaming is managed by the network, which uses the Xn interface for coordinated handovers [12].
- Empirical Data: In mobility tests with Autonomous Mobile Robots (AMRs), Wi-Fi 6 dropped over 1,800 packets due to re-association delays. In the same scenario, the Private 5G system only dropped 0-5 packets [10].
- Impact: A steel manufacturing case study reported that Wi-Fi instability caused 5-6 disconnects per week for outdoor cranes, risking \$90,000 in material loss per event. Private 5G deployment eliminated these disconnects [3].

### 3.3. Coverage Density

5G radios in the CBRS/n78 bands generally transmit at higher power (EIRP) than Wi-Fi. A techno-economic analysis showed that covering 1,000,000 sq. ft. of outdoor space requires 20 Wi-Fi access points, compared to only 4 private 5G access points [3].

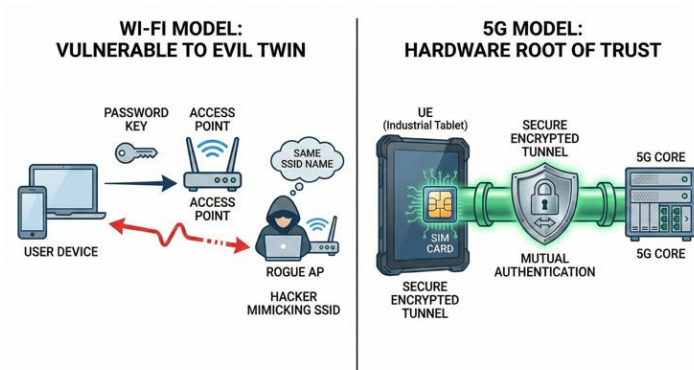
**Table 1: Summary of Empirical Performance Metrics [10] [11] [12]**

Metric	Wi-Fi 6 Performance	Private 5G Performance
Median Latency	3.7 - 4.7 ms	4.8 ms
Tail Latency (99.99%)	5.2 - 264 ms (Variable)	5.4 - 34.4 ms (Bounded)
Packet Loss (Mobility)	High (>1800 packets)	Low/Negligible (<5 packets)
Roaming Mechanism	Client-Initiated (Uncoordinated)	Network-Controlled (Seamless)

#### 4. Security Architecture

- Authentication Protocols: Wi-Fi 6 requires WPA3-SAE (Simultaneous Authentication of Equals), which combats offline dictionary attacks but remains a password-based exchange vulnerable to social engineering [13]. Private 5G depends on 5G-AKA (Authentication and Key Agreement), which uses a hardware-based root of trust (SIM/eSIM) [14].
- Trust Model: 5G enforces mutual authentication; the network must cryptographically verify its identity to the device before the device connects. This effectively prevents "Evil Twin" or "Rogue AP" attacks that threaten Wi-Fi environments [14].

- Privacy (SUCI): 5G introduces the Subscription Concealed Identifier (SUCI). Unlike previous generations, where the IMSI could be intercepted (e.g., via IMSI Catchers), 5G encrypts the device identity using the Home Network's public key before transmission [15].
- Segmentation: Wi-Fi uses logical VLANs sharing the same airtime. 5G employs Network Slicing, enabling physical resource reservation. Even if one slice becomes congested, critical traffic in another slice remains unaffected [11].



**Fig 2: Security Trust Models for Wi-Fi and 5G Technology**

#### 5. Energy Efficiency and Device Autonomy

For battery-powered IIoT sensors, energy consumption is a crucial factor. Both standards have implemented sleep modes to prolong battery life, but they function differently.

- Wi-Fi 6: Target Wake Time (TWT): TWT enables the Access Point and client to negotiate specific times to wake up and exchange data. This reduces contention and allows devices to remain in deep sleep for more extended periods [16].
- 5G: C-DRX and RRC Inactive: 5G uses Connected Mode Discontinuous Reception (C-DRX) to wake the device periodically to monitor the control channel (PDCCH) for data. Studies show that enabling C-DRX can cut User Equipment (UE) battery use by about 20% compared to an always-on connection [17].
- Comparative Analysis: While 5G provides better sleep management during active sessions, Wi-Fi 6 modems generally consume less baseline power than 5G cellular modems, which require more complex RF front-ends to support multiple bands. For simple, static IoT sensors that send infrequent data, Wi-Fi 6 with TWT often results in longer

battery life. For mobile and critical assets, the energy cost of 5G is offset by eliminating energy-intensive re-scanning and re-association during handovers [18] [19].

#### 6. Techno-Economic Analysis (TCO)

Contrary to the belief that 5G is too expensive, TCO models that account for density and downtime favor 5G for large facilities.

##### 6.1. Infrastructure and Capex

A study modeling the deployment of a steel plant (250,000 sq. ft. indoor, 1 million sq. ft. outdoor) compared costs [3]:

- Wi-Fi 6: Required 120 APs (100 indoor, 20 outdoor). Total 3-year cost: \$578,435 [3].
- Private 5G: Required 21 APs (17 indoor, 4 outdoor). Total 3-year cost: \$425,692 [3].
- Result: The 5G solution reduced total network costs by 26%, mainly by reducing cabling, switch ports, and installation labor [3].

## 6.2. Opex and ROI

The "Cost of Downtime" is a crucial factor. The manufacturing facility mentioned earlier faced annual losses of \$4.3 million due to Wi-Fi disconnects that interrupted production batches. By resolving these issues, the Private 5G network achieved an ROI payback period of approximately three months [3].

## 6.3. Generalized Model

A comprehensive academic study conducted by the University of Bristol confirmed these findings and developed a TCO model:

$$TCO_{5GNPN} = \sum Capex + \left( \sum Opex \right) \times N_{yrs}$$

The study found that 5G Non-Public Networks (NPN) utilizing Network Function Virtualization (NFV) can deliver 40% energy savings and up to 53% TCO savings compared to traditional deployments, especially when using Neutral Host models [20].

## 7. Vertical Use Case Analysis

Vertical-specific environmental constraints and operational risk profiles increasingly influence the choice between Wi-Fi 6 and Private 5G.

### 7.1. Mining and Heavy Industry: The Coverage Challenge

Open-pit mines and large industrial yards are among the most challenging environments for wireless connectivity.

- **Infrastructure Density:** A case study at the Boliden Kevitsa mine showed that Private 5G needed only 4 cellular access points to cover the pit area, whereas a Wi-Fi setup would have required at least 40 access points. In active blasting zones, maintaining 40 wired backhaul points is operationally infeasible [21].
- **Reliability:** Autonomous Haulage Systems (AHS) need continuous heartbeat connections. Wi-Fi's frequent handovers (every 50-100 meters) cause "micro-stops" in AHS trucks. Private 5G maintains connections over kilometer-wide cells, preventing handover-related stoppages [22].

### 7.2. Logistics and Ports: Overcoming Metal Interference

Ports are characterized by "canyons" of stacked metal containers that block and deflect signals.

- **Propagation Physics:** A deployment at Peel Ports (UK) used Private 5G to bypass the Faraday cage effect caused by metal cranes. While Wi-Fi signals quickly degraded in the cluttered environment, 5G signals (using strong encoding like LDPC) penetrated the container stacks effectively [23].
- **Result:** The port reported a tenfold increase in connectivity speed and reliability for terminal operating systems (TOS) and crane telemetry compared to the legacy Wi-Fi network [23].

### 7.3. Healthcare: Mission-Critical Mobility

- **Performance Benchmarks:** A JMIR study on a private 5G standalone medical network found

that mobile ward rounds achieved average downlink speeds of 790 Mbps and uplink speeds of 91 Mbps to support high-definition video. In contrast, remote ultrasound procedures required significantly lower bandwidth (~4.82 Mbps downlink) but relied on high network stability, maintaining an average delay fluctuation (jitter) of approximately 8 ms [24].

- **Mobility:** As patients are moved between wards, Wi-Fi devices often "stick" to the lobby AP. 5G's network-controlled handover ensures seamless telemetry transmission during patient transport [24].

## 8. Conclusion

The empirical evidence shows that while Wi-Fi 6 provides high peak throughput and cost efficiency for stationary, high-density environments, it does not provide the determinism necessary for Industry 4.0 mission-critical mobility. Private 5G delivers the bounded latency, seamless roaming, and enhanced security needed for operational technology. Furthermore, techno-economic analysis shows that for large-scale industrial sites, Private 5G can be a more cost-effective choice, delivering lower infrastructure costs and a quick return on investment by reducing costly operational downtime.

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