# The Impact of Private Wireless Networks on Improving Efficiency and Productivity in Logistics and Warehousing

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**Abstract:**
**The logistics and warehousing industry is experiencing a fundamental shift driven by "Industry 4.0" principles, requiring a move from manual, labor-intensive tasks to automated, data-driven operations. A key factor enabling this change is the deployment of Private Wireless Networks (PWNs), specifically using 3GPP-defined 4G LTE and 5G New Radio (NR) standards. This report assesses how PWNs impact operational efficiency and productivity in logistics facilities. By offering dedicated coverage, deterministic low latency, and high connection density, PWNs address the limitations of traditional contention-based connectivity. The analysis covers essential architectural elements, such as Non-Public Network (NPN) models and Citizens Broadband Radio Service (CBRS) spectrum, and evaluates strategic use cases, including Autonomous Mobile Robots (AMRs) and large-scale IoT asset tracking. Additionally, the report highlights the convergence of Operational Technology (OT) and Information Technology (IT), emphasizing protocols such as PROFINET over 5G, as well as emerging standards such as 5G RedCap. Economic analysis shows that despite higher upfront costs, Private 5G provides a strong Return on Investment (ROI) through notable improvements in asset speed, system uptime, and infrastructure integration.**

**Keywords: Private 5G, 4G LTE, 5G NR, Industry 4.0, Logistics, Warehousing, Ultra-Reliable Low Latency Communications (URLLC), RedCap, Citizens Broadband Radio Service (CBRS), Autonomous Mobile Robots (AMR), Industrial IoT.**

## I. INTRODUCTION

The modern supply chain faces intense pressure to increase throughput speed while reducing error rates. As e-commerce raises consumer expectations for same-day delivery, distribution centers (DCs) are becoming highly automated fulfillment hubs. In this environment, the primary bottleneck is often not mechanical capacity but connectivity. Traditional wireless solutions, primarily Wi-Fi, were designed for casual human use and often cannot meet the stringent reliability and low-latency requirements of mission-critical industrial machines. [1].

Private Wireless Networks (PWNs) have become the foundational infrastructure for the "smart warehouse." Unlike public cellular networks, a PWN is dedicated entirely to a specific enterprise, offering full control over network resources, data sovereignty, and security [2]. The move to 5G Standalone (SA) architecture further enhances this by adding features like Ultra-Reliable Low Latency Communications (URLLC) and Massive Machine Type Communications (mMTC). These features allow logistics operators to coordinate fleets of robots, deploy large sensor arrays, and use augmented reality (AR) tools with a reliability previously achievable only with wired connections [3].

## II. TECHNICAL ARCHITECTURE AND FUNDAMENTALS

To understand the productivity gains enabled by Private 5G, it is important to examine the technical architecture that sets it apart from consumer-grade solutions.

### A. Deployment Models: 3GPP Non-Public Networks (NPN)

The 3rd Generation Partnership Project (3GPP) defines Private Networks as Non-Public Networks (NPNs). There are two primary deployment models relevant to logistics [3] [4]:

1. Standalone Non-Public Networks (SNPN): This setup provides complete isolation. The enterprise manages its own Radio Access Network (RAN) and 5G Core (5GC), independent of public mobile network operators (MNOs). This guarantees that warehouse operations are protected from public network congestion or outages, ensuring maximum resilience and data privacy [3].
2. Public Network Integrated NPN (PNI-NPN): This configuration involves support from a public MNO, potentially sharing the RAN or Control Plane while keeping essential data traffic local through a User Plane Function (UPF). Although this lowers initial capital costs, it also creates dependencies on external operators [3].

### B. Spectrum Strategies: The Role of CBRS in the US

Access to radio spectrum is the lifeblood of wireless communication. In the United States, the Citizens Broadband Radio Service (CBRS) band (3.55–3.70 GHz) has democratized access to high-quality mid-band spectrum [5].

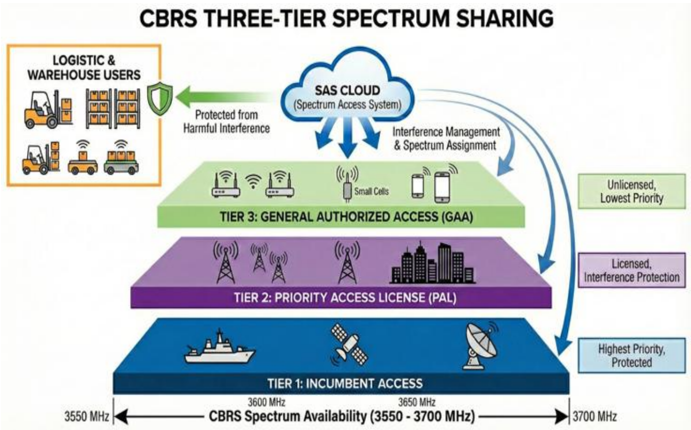


***Figure 1: Spectrum Access System (SAS) Hierarchy***

For logistics, the General Authorized Access (GAA) tier of CBRS enables warehouses to deploy private LTE and 5G networks without the high costs of leasing licensed spectrum. This "innovation band" provides the propagation characteristics needed to cover large indoor facilities and outdoor logistics yards with significantly fewer nodes than high-frequency Wi-Fi deployments [6].

### C. The 5G Core and Edge Computing

The transition to 5G Standalone (SA) introduces a Service-Based Architecture (SBA). A key feature for logistics is the separation of the Control Plane (CP) and User Plane (UP). This setup enables the UPF to be physically located "at the Edge"—inside the warehouse server room. For example, data from a Programmable Logic Controller (PLC) travels to the local radio, then to the local UPF, and directly to the local Warehouse Management System (WMS), resulting in round-trip latencies as low as 20ms without ever passing through the public internet [3] [7].

## III. STRATEGIC USE CASES DRIVING EFFICIENCY

Implementing Private 5G enables specific high-value applications that directly enhance logistics efficiency and productivity.

### A. Autonomous Mobile Robots (AMRs) and AGVs

The most significant productivity driver in modern warehousing is the automation of material transport.

- **Swarm Coordination:** Reliable connectivity enables the coordination of "swarms" of AGVs. Unlike magnetic-tape-guided vehicles, 5G-connected AMRs use Simultaneous Localization and Mapping (SLAM) navigation. High-bandwidth uplinks enable these robots to offload intensive processing to edge servers, reducing their weight and energy consumption. [8]

- **Velocity and Density:** Empirical data indicate that reliable low-latency connections enable AGVs to operate at higher speeds and with smaller safety buffers. Research shows that private wireless connectivity can enable mobile robotics to move faster than legacy connectivity solutions, directly boosting facility throughput [9].
- **Safety Integration:** The deterministic nature of 5G enables safety protocols (e.g., PROFIsafe) over the wireless link, allowing for immediate emergency stops if a hazard is detected, a capability often inconsistent on contention-based networks [10].

### B. Massive IoT and Real-Time Inventory Visibility

5G's mMTC capability supports connection densities of up to one million devices per square kilometer, far exceeding the capacity of Wi-Fi access points [11].

- **Asset Tracking:** Warehouses can deploy thousands of low-power sensors to monitor pallets, forklifts, and high-value inventory in real-time. This shifts operations from periodic physical inventory counts to "perpetual inventory" visibility, greatly reducing stockouts and "lost" items [12].
- **Environmental Monitoring:** Sensors that monitor temperature and humidity for cold-chain logistics can run for years on a single battery, reliably transmitting data over the private network to ensure compliance and minimize spoilage [13].

### C. Augmented Reality (AR) and Video Analytics

- **Vision Picking:** Warehouse workers using AR smart glasses see visual overlays for picking locations and quantities. This hands-free method boosts accuracy and speed. The high downlink bandwidth of 5G ensures schematics and overlays render smoothly, avoiding lag that can cause motion sickness and user fatigue [14].
- **Operational Optimization:** High-definition video cameras connected through 5G can feed AI analytics engines to identify bottlenecks or safety violations. In port logistics, such optimization has shown significant environmental benefits; for example, the Port of Livorno project used 5G to improve vessel berthing, resulting in an 8.2% decrease in $CO_2$ emissions per container terminal [15].

## IV. OT/IT CONVERGENCE AND IMPLEMENTATION CHALLENGES

Implementing Private 5G presents an Operational Technology (OT) integration challenge that involves bridging the gap between OT and Information Technology (IT).

### A. Bridging Legacy Protocols: PROFINET over 5G

Industrial environments depend heavily on Ethernet-based fieldbus protocols like PROFINET, which set strict jitter and cycle-time standards.

- **Protocol Conversion:** Industrial 5G routers act as gateways, encapsulating Layer 2 industrial Ethernet traffic for transmission over the 5G network [16].
- **Performance:** Testing shows that 5G can support PROFINET with cycle times as low as 4-8ms and jitter below 1ms, metrics that are hard to maintain on Wi-Fi due to its contention-based access method [1]. This allows for wireless control of Programmable Logic Controllers (PLCs) and mobile machinery.

### B. The Device Ecosystem and 5G RedCap

A historical obstacle to private network adoption has been the cost and complexity of 5G user equipment.

- **5G RedCap (Reduced Capability):** Introduced in 3GPP Release 17, RedCap fills the gap between high-speed 5G and low-speed NB-IoT. RedCap devices provide enough speed for video and industrial sensors (e.g., 150 Mbps downlink) while offering much lower complexity, smaller size, and longer battery life [17].
- **Impact:** The commercial availability of RedCap modules is likely to accelerate the deployment of affordable wireless sensors and wearables in logistics, lowering the overall cost of connecting large fleets of devices [18].

### C. Security Architecture

Security is a key reason for adopting private networks.

- **SIM-Based Authentication:** Private 5G uses physical or embedded SIMs (eSIM) for device authentication. This hardware-based mutual authentication is much more secure than password-based Wi-Fi credentials (WPA), removing common attack vectors [19].
- **Data Sovereignty:** In an SNPN deployment, data never leaves the facility's premises, ensuring that sensitive inventory information and proprietary operational metrics remain isolated from the public internet [6].

## V. ECONOMIC ANALYSIS AND RETURN ON INVESTMENT (ROI)

The financial justification for Private 5G moves from just comparing hardware to a comprehensive analysis of operational efficiency.

### A. Total Cost of Ownership (TCO)

While 5G radio nodes cost more per node than Wi-Fi access points, the better propagation characteristics of cellular technology mean far fewer nodes are needed.

- **Infrastructure Consolidation:** Coverage analysis shows that a private cellular network may need up to 10 times fewer nodes than a Wi-Fi network to cover the same large indoor and outdoor area [6]. This significantly reduces cabling, switch port requirements, and installation labor, resulting in a lower long-term TCO [20].

### B. Productivity Monetization

The main ROI comes from the "Cost of Inaction"—the costs associated with downtime and inefficiency.

- **Uptime Value:** In a high-volume fulfillment center, even a few minutes of network downtime can cause thousands of dollars in delayed shipments. The high reliability (up to "five nines" or 99.999%) of Private 5G helps prevent these costly disruptions [21].
- **Asset Utilization:** By enabling robots to move faster and optimizing the routing of reach stackers and forklifts, facilities can manage higher volumes without requiring additional space. Industry analysis shows that nearly 87% of organizations achieve a return on investment (ROI) within 12 months through energy savings, asset optimization, and increased efficiency [22].

## VI. CONCLUSION

The integration of Private Wireless Networks into logistics represents a major shift in supply chain operations. By overcoming the unpredictable limitations of traditional connectivity with deterministic scheduling and reliable coverage, Private 5G enables the full potential of autonomous robotics, extensive IoT, and workforce productivity. The development of the device ecosystem with 5G RedCap and the availability of shared spectrum options, such as CBRS in the United States, are reducing barriers to entry. For logistics stakeholders, deploying Private Wireless infrastructure is crucial for creating a fully autonomous, highly efficient, and sustainable warehouse of the future.

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