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Original Article

Enhanced Retail Experience Powered by Private Wireless: Architectures, Applications, and Performance Analysis

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***Abstract** - The retail industry is at a critical turning point, shifting from traditional brick-and-mortar operations to "Retail 4.0" a model characterized by the seamless integration of physical and digital environments. This "physical" transformation demands a robust connectivity infrastructure capable of supporting mission-critical applications such as autonomous logistics and immersive Augmented Reality (AR) customer experiences. This research paper provides a comprehensive technical analysis of Private 5G (P5G) networks as the key enabler for this enhanced retail experience. We examine specific architectural deployments defined by 3GPP Release 16 and 17, specifically comparing Stand-Alone Non-Public Networks (SNPN) with Public Network Integrated NPNs (PNI-NPN) in terms of retail scalability and data sovereignty. Through an in-depth comparison with Wi-Fi 6, this report demonstrates that Private 5G offers better determinism, supporting ultra-low latency (<10ms) and high device density (10^6 devices/km²) necessary for advanced inventory tracking and robotic automation. Additionally, we analyze how network slicing can help achieve Payment Card Industry Data Security Standard (PCI-DSS) compliance, ensuring secure, instantaneous transactions across the retail space. The paper concludes that Private 5G is more than just a connectivity upgrade it's a strategic asset that unlocks trillions in economic value by enabling real-time, data-driven optimization of the entire retail supply chain.*

***Keywords** - Private 5G, Retail 4.0, Network Slicing, Augmented Reality (AR), Intelligent Warehousing, 3GPP Release 17, Mobile Edge Computing (MEC), PCI-DSS Compliance, SNPN, Ambient IoT, Autonomous Mobile Robots (AMR), Physical Integration.*

1. Introduction

1.1. The Paradigm Shift to Retail 4.0

The global retail industry is undergoing a significant transformation driven by shifting consumer behaviors and the ongoing push for operational efficiency. The traditional linear supply chain and fixed in-store experience are shifting toward dynamic, interconnected ecosystems where data continuously flows among manufacturers, distribution centers, and the retail edge [1]. This shift, called "Retail 4.0," aims to eliminate friction between online and offline shopping, creating a "physical" environment where physical presence is enhanced by digital ubiquity. According to the McKinsey Global Institute, integrating advanced connectivity in retail and related logistics could create between $420 billion and $700 billion in global value by 2030 [1]. This value stems from improved customer engagement, such as personalized wayfinding and virtual try-ons, as well as from optimizing inventory management and warehouse operations behind the scenes. However, realizing this potential requires a network infrastructure that offers more than just connectivity; it demands "relentless reliability," deterministic performance, and built-in security [2].

1.2. Limitations of Incumbent Wireless Technologies

Over the past 20 years, retail connectivity has mainly fallen into two categories: Wi-Fi (IEEE 802.11) for local-area networks and public cellular networks for wide-area coverage. While Wi-Fi 6 (802.11ax) introduces improvements such as Orthogonal Frequency-Division Multiple Access (OFDMA) to support more devices, it remains limited by operating in unlicensed spectrum [3]. The "Listen-Before-Talk" (LBT) mechanism inherent to Wi-Fi introduces variable latency (jitter) as network load increases, leading to unpredictable performance unsuitable for safety-critical applications such as Autonomous Mobile Robots (AMRs) [4]. Furthermore, public cellular networks often lack sufficient indoor penetration for large "big box" retailers and raise data privacy concerns by routing traffic through the Mobile Network Operator's (MNO) core. Retailers need a solution that combines the mobility and coverage of cellular technology with the control and privacy of a Local Area Network (LAN) [5].

1.3. The Promise of Private 5G

Private 5G, or Non-Public Networks (NPN) as defined by 3GPP, addresses these gaps by dedicating spectrum and infrastructure to a specific enterprise. This allows retailers to customize network settings, such as the Uplink/Downlink ratio in Time Division Duplex (TDD) frames, to meet their specific traffic needs, such as high-uplink video analytics [5] [6].

This paper examines the four pillars of the enhanced retail experience driven by Private 5G:

1. Seamless Physical/Digital Integration: Leveraging 5G positioning and Edge Computing for AR.
2. Advanced Inventory Management: Utilizing massive Machine-Type Communications (mMTC) for real-time visibility.
3. Personalized Guidance: Context-aware navigation and interaction.
4. Instant Transactions: Secure mobile Point-of-Sale (mPOS) systems through network slicing.

1.4. Technical Architecture of Private 5G in Retail

Implementing Private 5G in a retail environment is complex; it involves selecting the right architectural model based on the company's needs for control, cost, and coverage. The 3GPP Release 16 and 17 standards provide the framework for these Non-Public Networks (NPNs).

1.5. Deployment Models: SNPN vs. PNI-NPN

Retailers must choose between operating a fully independent network or integrating with a public carrier. This decision fundamentally impacts the network's logical and physical topology [7].

1.6. Stand-Alone Non-Public Network (SNPN)

In the SNPN model, the retailer operates independently. The entire network stack, Radio Access Network (RAN), Control Plane (CP), and User Plane Function (UPF), is deployed either on-premises or in a private cloud, completely isolated from the public PLMN [7].

- Architecture: The network is identified by a combination of a PLMN ID and a Network ID (NID), which prevents user equipment (UE) such as scanners and tablets from accidentally roaming onto public networks [7].
- Retail Implication: This model provides the highest level of security and data control, making it ideal for large Distribution Centers (DCs) handling trade secrets or high-value inventory. It removes dependencies on third parties, ensuring that a public network outage does not stop warehouse operations [7].
- Challenges: It needs significant in-house technical skills or a managed service provider (MSP) to run the network.

2. Public Network Integrated NPN (PNI-NPN)

The PNI-NPN model involves deploying a private network alongside a public Mobile Network Operator (MNO). This is often achieved through a "Shared RAN" approach, where the base stations (gNodeBs) broadcast both the public PLMN ID and a Closed Access Group (CAG) ID for the private enterprise [6] [7].

- Architecture: Data traffic for the retailer is routed locally through a Local Breakout (LBO) to an on-premises UPF, while the MNO’s central core may handle control-plane signaling [6].
- Retail Implication: This reduces Capital Expenditure (CAPEX) because the retailer can utilize the MNO's spectrum and existing tower infrastructure. It is especially suitable for chain retail stores where deploying a full 5G Core at each location would be too costly. It also supports seamless roaming for logistics fleets entering and leaving the facility [6].
- CAG Implementation: The Closed Access Group feature (introduced in Release 16) ensures that only authorized devices, such as staff tablets and IoT sensors, can access the specific radio resources allocated to the store, preventing customers on the public network from congesting the private slice [7] [8].

2.1. Spectrum Strategies: The Lifeblood of Connectivity

The performance of a private network depends on the spectrum it uses.

- CBRS (3.5 GHz) in the US: The Citizens Broadband Radio Service offers a "Goldilocks" spectrum for retail, providing better propagation than 5 GHz Wi-Fi while allowing private ownership through General Authorized Access (GAA) or Priority Access Licenses (PAL) [9] [10].
- Industrial Bands (3.7–3.8 GHz): Countries like Germany have allocated specific spectrum for industry, allowing retailers to deploy high-power networks without interference from public carriers [11].
- mmWave (24 GHz+): For ultra-high-density areas, such as checkout zones in a flagship store, mmWave provides massive bandwidth (gigabits per second) but has limited penetration. It is usually deployed as a "capacity booster" in specific zones [12].

2.2. Multi-Access Edge Computing (MEC) Integration

At the heart of the "enhanced experience" is the concept of MEC. By placing compute resources near the Private 5G Core (specifically the UPF), retailers can attain end-to-end latencies below 10ms [13].

- Mechanism: Traffic from a smart mirror or an AMR is routed by the UPF to a local server instead of the internet. This "hairpinning" of traffic is essential for AR rendering and real-time robotic control [14].
- Benefit: This architecture not only reduces latency but also keeps sensitive video analytics data within the physical premises, addressing privacy compliance (GDPR/CCPA) concerns [14

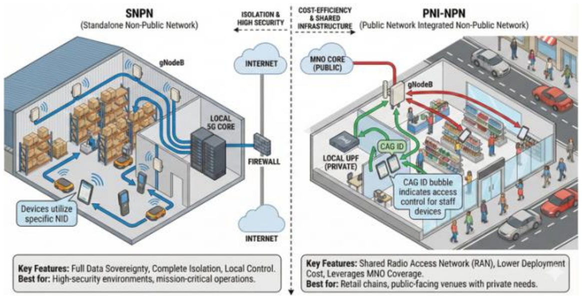

Fig 1: Comparing SNPN and PNI-NPN Private 5G Retail Architecture Topologies

3. Seamless Physical/Digital Integration Via Embb

The modern retail floor is becoming a platform for digital interaction. The "Enhanced Mobile Broadband" (eMBB) slice of 5G is what drives this immersion.

3.1. Augmented Reality and the Latency Budget

Augmented Reality (AR) in retail involves uses such as wayfinding overlays, product information pop-ups, and gamified shopping experiences. However, the quality of experience (QoE) in AR is heavily influenced by the "motion-to-photon" latency—the delay between a user's head movement and the display update [15].

- The Threshold: Research indicates that latency should stay below 20ms to prevent motion sickness and ensure immersion [15].
- Split Rendering Architecture: Mobile devices, such as smart glasses or phones, often lack the GPU power to render high-quality 3D assets. "Split rendering" delegates this task to an MEC server. The device transmits tracking data (uplink), the server renders the frame, and streams it back (downlink) [11] [16].
- 5G Necessity: This loop requires a stable, high-bandwidth uplink and a low-latency downlink. Wi-Fi's contention-based access often causes jitter spikes >20ms in crowded environments, disrupting the experience. Private 5G, using prioritized QoS flows (5QI), ensures the packet delivery needed for smooth AR [17].

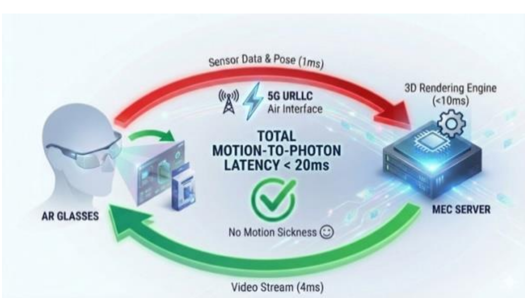

Fig 2: A Private 5G Network Deployed With Edge Applications on an MEC Server to Support Augmented Reality

3.2. Smart Mirrors and High-Bandwidth Interactivity

Smart mirrors let customers "try on" clothes virtually. These devices are data-heavy, requiring streaming of 4K textures and uploading real-time volumetric video for body tracking [18].

- Bandwidth Consumption: A single interactive 3D mirror uses 50–100 Mbps. A flagship store with 20 mirrors could overload a standard Wi-Fi network, causing connectivity issues for POS systems [12].
- Immersive Booths: Newer concepts like "Immersive Phone Booths" offering 360-degree video streaming require even higher throughput, which 5G's wide channel bandwidths (up to 100 MHz in sub-6 GHz) can easily support [12].

3.3. Precision Positioning and Navigation

GPS is ineffective indoors. Retailers need accurate location data to help customers find specific items on shelves.

- 3GPP Enhancements: Releases 16 and 17 introduced advanced positioning techniques, including Round-Trip Time (RTT), Angle of Arrival (AoA), and Time Difference of Arrival (TDOA) [19].
- Accuracy: Private 5G networks, due to their dense small-cell deployments, can achieve sub-meter positioning accuracy. This enables "NavMesh" applications where an AR arrow on the customer's phone points directly to the specific aisle and shelf bin for a product [20].

4. Advanced Inventory Management: The Silent Revolution

While customer experience is visible, the most significant financial benefit of Private 5G lies in "Intelligent Warehousing" and inventory optimization.

4.1. The Cost of Inaccuracy

Traditional inventory methods, which rely on manual barcode scans or periodic cycle counts, result in data delays. Even a system that is 95% accurate can result in millions of dollars in lost revenue due to "ghost inventory" (system shows in stock, but the shelf is empty) or stockouts. These inefficiencies are estimated to cost $3.7 million per warehouse annually. [21].

4.2. Massive Machine-Type Communications (mMTC) and RFID

Private 5G unlocks the full potential of RFID (Radio Frequency Identification) by serving as a high-capacity backhaul for a dense network of readers.

- Scale: 5G's mMTC slice supports connection densities of up to 1 million devices per square kilometer [22]. This enables retailers to install fixed RFID readers on every shelf, creating a "Smart Shelf" ecosystem.
- Real-Time Visibility: Unlike handheld scanners,

smart shelves offer continuous monitoring. When a product is taken, the inventory system updates immediately. This data stream enables predictive replenishment, where orders are initiated before stock depletes [21].

4.3. Ambient IoT and Zero-Energy Devices

Looking ahead, the "Ambient IoT" is seen as the next frontier. Supported by the Ambient IoT Alliance and 3GPP Release 19 studies, it involves battery-less tags that harvest energy from 5G radio waves to transmit small status packets [23].

- Implication: This could remove the cost barrier of active tags, enabling each yogurt cup or t-shirt to directly communicate its presence and temperature status to the Private 5G network, ensuring freshness and reducing spoilage [21] [23].

4.4. Robotic Automation (AMRs and AGVs)

Autonomous Mobile Robots (AMRs) are increasingly employed for picking and packing tasks. Their efficiency depends directly on network performance.

- The Roaming Problem: In a Wi-Fi environment, an AMR moving between access points must disconnect and re-associate. This "handoff" can take hundreds of milliseconds, slowing or stopping the robot to ensure safety [24].
- 5G Mobility: 5G manages mobility at the base station level (Xn interface). Handovers are nearly seamless (0ms interruption), enabling AMRs to move at full speed throughout the facility without hesitation [6].
- Off-Board Intelligence: The ultra-low latency of Private 5G (<10ms) allows retailers to offload the robot's navigation intelligence (SLAM - Simultaneous Localization and Mapping) to the Edge Server. This makes the robots more affordable (with less onboard compute) and lighter (with less battery), significantly reducing the cost of automation fleets [24] [25].

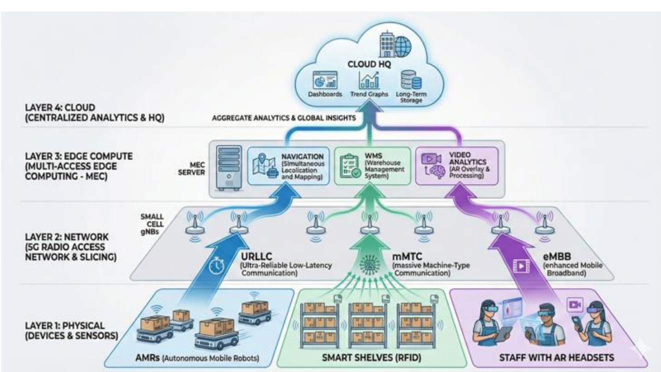

Fig 3: Multi-Slice Private 5G Architecture Supporting Different Warehouse Applications

5. Instant Transactions and Security Compliance

The checkout line is often where sales are lost due to friction. Private 5G enables "Instant Transactions" through secure, compliant, and widespread mobile Point-of-Sale (mPOS) systems.

5.1. The PCI-DSS Challenge

Retailers must comply with the Payment Card Industry Data Security Standard (PCI-DSS). Version 4.0 highlights strict network segmentation and safeguarding of cardholder data [26].

- Wi-Fi Vulnerabilities: Achieving true segmentation on Wi-Fi is challenging, often relying on VLANs over a shared wireless network. This approach is vulnerable to "sniffing" attacks if encryption keys are compromised [27].
- 5G Native Security: Private 5G uses the SIM (or eSIM) as a hardware root of trust. The Authentication and Key Agreement (AKA) protocol ensures mutual authentication, verifying the POS device and confirming its trust in the network, thus preventing "Evil Twin" attacks common in Wi-Fi [27].

5.2. Network Slicing for Compliance

Network slicing is the "killer app" for compliance. It enables the retailer to create a logically isolated network instance specifically for transactions.

- Isolation: The "POS Slice" is isolated from the "Guest Wi-Fi" and "CCTV" slices. This separation extends from the radio resource block to the core network function. Even if the Guest network is subjected to a Distributed Denial of Service (DDoS) attack, the POS slice remains unaffected because its resources are reserved [28].
- Encryption: 5G standards require strong encryption (128-bit/256-bit) for user-plane traffic, meeting PCI-DSS requirements for data in transit without the need for complex overlay VPNs on each device [29].

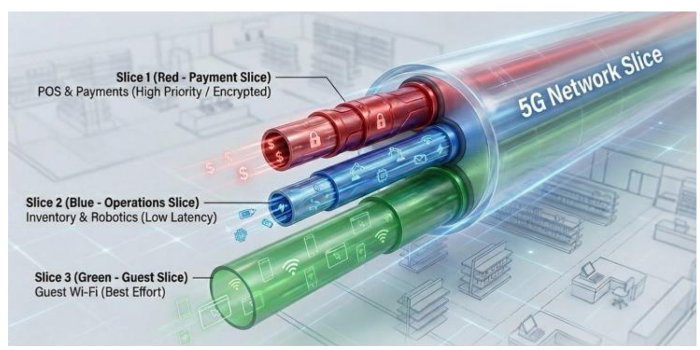

Fig 4: 5G Network Slicing for Secure Transactions

5.3. Ubiquitous Coverage for mPOS

Sales associates with mPOS tablets must be able to process transactions everywhere—from fitting rooms to curbside pickup areas.

- Dead Zones: Wi-Fi often faces coverage gaps between access points or in areas with high interference [30] [31].
- 5G Consistency: Private 5G, especially in sub-6 GHz bands, offers better signal propagation and reliability. This ensures that transactions occur instantly, regardless of the customer's location, reducing "queue anxiety" and increasing throughput [30] [31].

6. Comparative Analysis: Private 5G vs. Wi-Fi 6/6E

While Wi-Fi 6 is a capable technology for general-purpose IT, it falls short of the operational technology (OT) requirements needed for an enhanced retail experience.

6.1. Performance Metrics Comparison

Table 1: Technical Comparison of Private 5G and Wi-Fi 6 in Retail Environments [4]

Feature	Private 5G (Rel 16/17)	Wi-Fi 6 / 6E (802.11ax)	Impact on Retail Operations
Spectrum Access	Scheduled (Deterministic): The base station dictates exactly when each device transmits.	Contention (Probabilistic): Devices compete for airtime (Listen-Before-Talk).	5G guarantees latency for AMRs; Wi-Fi suffers jitter in crowded stores.
Interference	Low: Licensed or coordinated shared spectrum (CBRS/SAS).	High: Unlicensed spectrum shared with neighboring stores and consumer hotspots.	5G provides a "clean" RF environment for mission-critical POS.
Reliability	99.999% (Five Nines): Built for industrial-grade uptime.	Best Effort: Variable based on congestion.	Essential for safety systems and continuous inventory tracking.
Latency	< 10ms (Ultra-Low): Stable and bounded.	20-40ms (Variable): Can spike to 100ms+ under load.	5G enables nausea-free AR and precise robot control.
Mobility (Handoff)	Seamless (0ms): Device-assisted, network-controlled handover.	Break-before-Make: Roaming relies on client decision; noticeable connection drops.	5G allows robots and staff to move freely without disconnects.
Coverage Radius	Large (Hundreds of meters): Better penetration.	Short (Tens of meters): Requires dense AP grid.	5G reduces infrastructure clutter (cabling, switch ports) in large warehouses.
Security	SIM-based: Hardware root of trust; Slice isolation.	WPA3: Password/Certificate based; harder to segment.	5G simplifies PCI-DSS compliance via inherent slicing.

6.2. The Density and TCO Equation

In high-density settings like flagship stores, the large number of devices (smartphones, watches, sensors) can overwhelm a Wi-Fi network due to signaling overhead. 5G's control plane is designed to manage this "signaling storm," supporting 1 million devices/km² [22].

- Total Cost of Ownership (TCO): Although 5G access points (Small Cells) are more expensive individually than Wi-Fi APs, their superior coverage means fewer are needed. For a large distribution center, a Private 5G deployment can require 3-4 times fewer radios than a comparable Wi-Fi setup, significantly cutting cabling and installation costs [32].

7. Future Directions: 3GPP Release 17 and Beyond

The capabilities of Private 5G are constantly expanding. Release 17 (finalized in 2022) and the upcoming Release 18 (5G Advanced) introduce features specifically designed for the retail and enterprise sectors.

7.1. Reduced Capability (RedCap) NR

Not every retail device requires gigabit speeds. Release 17 introduces "RedCap" (or NR-Light), a new category of 5G devices that are simpler, more affordable, and more energy-efficient than smartphones [19].

Use Case: RedCap is perfect for advanced mobile scanners, wearable staff communicators, and wireless security cameras. It bridges the gap between high-end eMBB and low-end IoT, enabling these mid-tier devices to benefit from 5G slicing and reliability without needing a full 5G modem [19].

7.1. Sidelink and Device-to-Device Communication

Release 17 improves "Sidelink," allowing devices to communicate directly with each other without routing data through the base station [33].

Retail Application: A "swarm" of inventory drones could coordinate their flight paths locally using Sidelink to avoid collisions, or smart shelves could create a local mesh to collect data before sending a single update to the network, conserving uplink capacity [34].

7.2. 5G LAN-Type Services

To simplify the migration of legacy retail applications (which often rely on Layer 2 Ethernet protocols), Release 16 and 17 support "5G LAN-type services" [35]. This enables the 5G network to emulate a virtual Ethernet switch, allowing retailers to migrate their existing inventory systems to 5G without rewriting their IP addressing schemes or applications.

8. Conclusion

The "Enhanced Retail Experience" isn't a distant future concept; it's an immediate operational need driven by the merging of physical and digital commerce. Private 5G networks serve as the essential backbone for this shift, offering a unique combination of high bandwidth, predictable low latency, and large connection capacity that older technologies can't match. By adopting architectures like SNPN or PNI-NPN, retailers gain the control needed to run mission-critical applications, from "Intelligent Warehousing" that prevents stockouts to the "Physical" AR experiences that engage shoppers. The ability to segment the network ensures that a surge in customer activity never compromises transaction security or the safety of autonomous robots. As the ecosystem advances with 3GPP Release 17 devices and the growth of Ambient IoT, Private 5G will become the invisible, reliable backbone of retail, transforming stores into fully programmable, responsive, and secure environments.

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