Private Wireless Networks in Smart Cities: Architectures, Performance Analysis, and Deployment Strategies

Rahul Bangera, Ellicott City, MD, USA.
Email: rahulmbangera@gmail.com

Abstract— **The development of the "Smart City" concept has historically been limited by public cellular networks and the fragmentation of unlicensed connectivity standards. As cities transition from passive data collection to active, real-time automation, the need for deterministic latency, enhanced security, and widespread coverage has driven the adoption of a new architectural approach. This paper explores the emerging role of Private Wireless Networks (PWNs), particularly Private 5G (P5G) and Private LTE, which utilize shared-spectrum frameworks like the Citizens Broadband Radio Service (CBRS) as the foundation for future urban management. Through a comprehensive technical comparison, this study demonstrates that Private 5G surpasses Wi-Fi 6 and LoRaWAN in mission-critical applications, especially those requiring mobility and ultra-reliable low-latency communication (URLLC). Additionally, we review key deployments in Las Vegas (USA), Sunderland (UK), Liverpool (UK), Tucson (USA), and Brownsville (USA) to assess tangible impacts on traffic management, digital inclusion, public safety, and autonomous logistics. The research concludes that, despite regulatory and integration challenges, transitioning toward municipal "micro-operators" and neutral host architectures offers a viable path for sustainable, sovereign, and scalable smart city connectivity.**

Keywords: Private 5G, Private LTE, CBRS, Smart Cities, Industrial Internet of Things (IIoT), Wi-Fi 6, LoRaWAN, Connected and Automated Logistics (CAL), Network Slicing, Municipal Infrastructure.

I. INTRODUCTION

The modern urban environment is a growing, complex system of interconnected components, including traffic management, public safety, utilities, and social services. The efficiency of these systems relies heavily on the underlying connectivity infrastructure. Historically, smart city projects have used a hybrid model that combines public cellular networks (3G/4G/5G) for widespread coverage and Wi-Fi for high-speed local access. However, this traditional approach is reaching significant limits in scalability and performance. Public networks, mainly built for consumer mobile broadband, often fail to ensure the Quality of Service (QoS) and uplink capacity needed for data-intensive municipal tasks such as HD video surveillance and autonomous vehicle telemetry [1] [2]. Meanwhile, Wi-Fi operating in unlicensed bands is vulnerable to interference and handover delays, which reduce reliability outdoors [1].

The emergence of Private Wireless Networks (PWNs) offers a new approach to municipal connectivity. These are dedicated networks that use LTE or 5G standards, are privately owned or operated by non-MNO (Mobile Network Operator) organizations, and enable cities to customize network settings to meet specific civic needs [1]. With new spectrum-sharing models like the 3.5 GHz CBRS band in the U.S. and Shared Access Licenses in the U.K., municipalities can reduce the high operational costs of commercial data plans while maintaining control over their data [3].

This paper aims to provide a detailed technical review of PWNs in the context of smart cities. Section II explains the architecture and spectrum basics. Section III compares the performance of different enabling technologies. Section IV presents real-world case studies demonstrating network performance. Finally, Sections V and VI discuss the challenges and future opportunities for municipal private wireless networks.

II. ARCHITECTURAL FRAMEWORK AND SPECTRUM PARADIGMS

A. Private 5G and LTE Architecture

The architecture of a private 5G network in a municipal setting typically follows 3GPP Releases 15 and 16, deploying dedicated Radio Access Network (RAN) and Core Network components that are localized to the city's infrastructure [1].

1. Standalone (SA) vs. Non-Standalone (NSA): While early deployments used NSA architectures based on 4G LTE cores, modern smart city implementations are increasingly adopting 5G Standalone (SA) architectures. SA networks eliminate reliance on legacy LTE control planes, enabling advanced 5G features like Network Slicing [4].

2. Mobile Edge Computing (MEC):
To meet the latency needs of applications like

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autonomous logistics, processing power is decentralized. In the Las Vegas deployment, edge compute nodes handle video analytics locally within the "Innovation District," reducing backhaul load and enhancing privacy by limiting the transmission of raw data [5].

B. Spectrum Access Models

The democratization of spectrum is the primary catalyst for municipal PWNs.

1. Citizens Broadband Radio Service (CBRS) - USA: The FCC's three-tiered sharing framework for the 3.55–3.70 GHz band has played a key role.
    - **Tier 1: Incumbent Access:** Protects existing military radars and satellite stations.
    - **Tier 2: Priority Access License (PAL):** Cities or enterprises bid for renewable licenses that guarantee interference protection.
    - **Tier 3: General Authorized Access (GAA):** Open access for any user, similar to Wi-Fi but using cellular technology. Cities like Tucson and Las Vegas have heavily relied on GAA for affordable wide-area coverage [3] [6] [7].

Figure 1: CBRS Spectrum Access Hierarchy

2. **Local Shared Access - UK/Europe:** Regulators like Ofcom (UK) have allocated spectrum (e.g., 3.8–4.2 GHz) for local licensing. This enables organizations to deploy private networks without depending on MNO spectrum assets, as demonstrated in the Sunderland and Liverpool deployments [8] [9].

III. COMPARATIVE TECHNOLOGY ANALYSIS

Selecting the right connectivity standard requires balancing coverage, capacity, latency, and cost.

A. Private 5G vs. Wi-Fi 6

While Wi-Fi 6 (802.11ax) introduces features like OFDMA to enhance density, it remains fundamentally an unlicensed technology subject to contention. Research comparing Private 5G LANs with Wi-Fi 6 in industrial settings found that, although Wi-Fi 6 provides high peak throughput, it suffers from significant jitter and packet loss under load, especially during mobility events (handover between access points) [1] [10].

In contrast, Private 5G demonstrated "deterministic" performance. Centralized scheduling in cellular networks ensures that critical packets are prioritized, maintaining low latency even in congested environments. This is crucial for applications like the teleoperation of autonomous trucks, where a latency spike could cause a safety incident [11].

Table 1: Technical Comparison of Connectivity Standards for Smart Cities [1] [10] [12]

Feature	**Private 5G (SA)**	**Wi-Fi 6 (802.11ax)**	**LoRaWAN**
Spectrum	Licensed / Shared (3.5/3.8 GHz)	Unlicensed (2.4/5/6 GHz)	Unlicensed (Sub-GHz)
Access Method	Scheduled (Deterministic)	Contention (CSMA/CA)	ALOHA (Random)
Mobility	Seamless (>100 km/h)	Limited (Break-before-make)	Supported (Low speed)
Coverage Radius	~1–5 km per node	~50–100 m per node	~10–15 km per gateway
Latency	Ultra-Low (1–10 ms)	Variable (10–50+ ms)	High (Seconds)
Throughput	High (Gbps Uplink/Downlink)	High (Gbps)	Very Low (<50 kbps)
Security	SIM/eSIM, 256-bit Encryption	WPA3	AES-128

B. The Role of LPWAN

Regarding sensor density, technologies such as LoRaWAN remain relevant. They are optimized for "Massive IoT" (mMTC)—devices with 10-year battery life transmitting small packets (e.g., waste bin sensors). As shown in Table 1, LoRaWAN complements Private 5G; it cannot support video or voice, but it manages the high-volume, low-data connections that would be spectrally inefficient on a 5G network [12]. Cities like Sunderland use a hybrid model, running LoRaWAN for static IoT alongside 5G for mission-critical applications [8] [13].

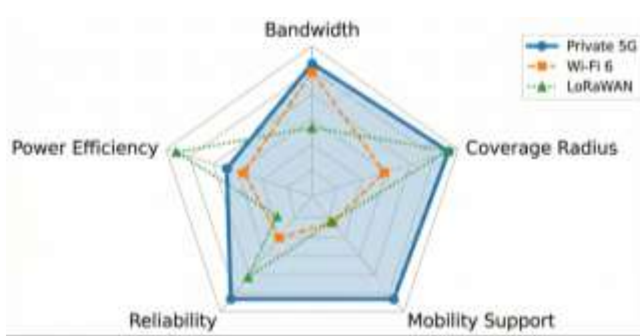

Figure 2: Comparison of Private 5G, Wi-Fi 6 and LoRaWAN Technologies

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IV. STRATEGIC USE CASES AND DEPLOYMENT CASE STUDIES

The following case studies demonstrate how technical skills drive municipal operational outcomes.

A. Autonomous Logistics and Transport: Sunderland, UK

Sunderland has positioned itself as a leader in smart city innovation through its partnership with Boldyn Networks [8] [14].

- **Implementation:** The city deployed a private 5G network using the n77 band (3945 MHz) and "XRAN" (Extended Radio Access Network) technology [15].
- **Use Case - 5G CAL:** The "5G Connected and Automated Logistics" pilot involved operating a 40-ton autonomous Heavy Goods Vehicle (HGV) delivering parts for Nissan. The private 5G network was crucial for enabling the "teleoperation" safety protocol, which allowed a remote driver to immediately take control of the HGV if the autonomous system encountered an unknown scenario [16] [17].
- **Outcome:** The project successfully validated the removal of the safety driver from the vehicle, demonstrating the feasibility of "Last Mile" logistics automation. The network also supports the "Sunderland Advanced Mobility Shuttle" (SAMS), a self-driving public transport service operating on public roads [15] [16].

B. Traffic Management and Economic Growth: Las Vegas, USA

The City of Las Vegas launched the largest open-access municipal-private 5G network in the U.S., using the CBRS spectrum [5] [18].

- **Implementation:** The network uses Juniper ACX7024 routers for backhaul and a Private 5G LAN architecture provided by NTT DATA and Celona. It spans the "Innovation District" and is expanding city-wide [5] [19].

- **Use Case - Intelligent Traffic:** The network links traffic signals and sensors to an Edge AI platform. This enables real-time analysis of traffic flow and pedestrian safety without sending data to a central cloud [5].
- **Outcome:** The city reports over $1 million in annual savings from improved patrols and reduced wrong-way accidents and collisions. Additionally, the network supports the "Loop" underground transit system, providing connectivity for Tesla's autonomous fleet [5] [20].

C. Health and Social Care: Liverpool, UK

The Liverpool 5G Create project focuses on using 5G technology to combat social deprivation and health disparities [4].

- **Implementation:** A 5G Standalone (SA) network was deployed using mmWave and sub-6 GHz shared spectrum on street furniture (lamp posts), specifically targeting low-income areas [4].
- **Use Case - Remote Care:** The network connected care homes to pharmacies through "Push-to-Talk" systems and facilitated remote monitoring of elderly residents using "Vitalerter" sensors [4].
- **Outcome:** The "Vitalerter" system lowered falls and reduced the need for disruptive nightly checks, leading to an estimated annual cost savings of £7,737 per user. Additionally, the project reported a 25% reduction in loneliness among users connected through the private network [21] [22].

D. Bridging the Digital Divide: Tucson, USA

Tucson leveraged the COVID-19 pandemic to accelerate its smart city initiative, focusing on digital equity [6] [23].

- **Implementation:** The city deployed a Private LTE network using CBRS GAA spectrum to avoid the high costs of fiber-to-the-home and commercial cellular plans [6] [23].
- **Use Case - Education:** The network was designed to provide internet access from municipal buildings to students' homes in underserved areas. The city handed out thousands of CBRS gateway devices (CPEs) to receive the signal [6] [23].
- **Outcome:** This approach enabled the city to function as its own ISP for low-income residents, ensuring reliable connectivity for remote learning and essential services without monthly data fees [23].

E. Public Safety and Smart Infrastructure: Brownsville, USA

Brownsville, Texas, once listed as one of the "least connected" cities in the United States, has initiated a major digital transformation with a private 5G deployment [24] [25].

- **Implementation:** In partnership with NTT DATA and Nokia, the city deployed a Private 5G (P5G) Radio Access Network (RAN) using CBRS spectrum. The network creates a "connective mesh" covering downtown, public parks, and key municipal facilities, such as the Department of Public Works yard [24] [25].
- **Use Case - Smart Parks and Safety:** The network enables real-time analysis of data from IoT sensors and cameras. Primary uses include monitoring park occupancy, managing crowds, and public safety surveillance. The high bandwidth and low latency of 5G allow for edge processing of video feeds, resulting in faster response times for city officials and law enforcement [26] [27].

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- **Outcome:** The deployment is transforming Brownsville into a technology hub, supporting the city's rapid growth driven by the nearby SpaceX Starbase. It has improved public space management and is well-positioned to attract new business opportunities by providing strong municipal connectivity [25] [26].

Table 2: Summary of City Private Wireless Deployments

City	Primary Technology	Spectrum	Key Application	Quantified Outcome
Sunderland	Private 5G (XRAN)	Shared (n77)	Autonomous Logistics	Validated driverless teleoperation [16] [17]
Las Vegas	Private 5G/LTE	CBRS (3.5 GHz)	Traffic & Public Safety	>$1M annual savings in safety ops [20]
Liverpool	5G Standalone	Shared (3.8 GHz)	Health & Social Care	£7,737 savings per care home user [21] [22]
Tucson	Private LTE	CBRS (GAA)	Digital Divide	Connectivity for thousands of students [6] [23]
Brownsville	Private 5G	CBRS	Smart Parks & Safety	Transformation to regional tech hub [25] [26]

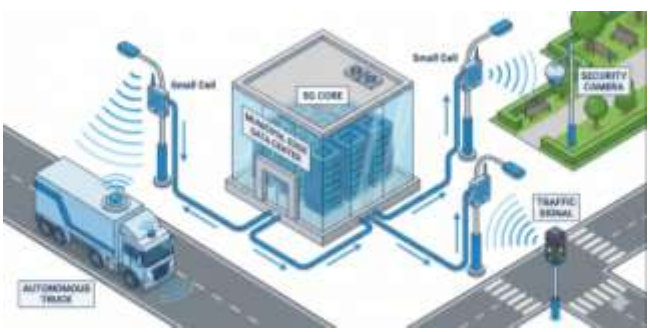

FIGURE 3: SMART CITY PRIVATE 5G NETWORK ARCHITECTURE

V. IMPLEMENTATION CHALLENGES AND REGULATORY LANDSCAPE

While the benefits are clear, major obstacles still exist for widespread adoption.

A. Spectrum Interference and Management

The reliance on shared spectrum, especially the GAA tier of CBRS in the US, introduces the risk of interference. Unlike PAL (Priority Access License) holders, GAA users lack interference protection. In dense urban areas where multiple entities deploy GAA networks, the noise floor can increase, degrading performance. Although Spectrum Access Systems (SAS) automatically assign channels to reduce this, congestion events have been recorded in early trials [28] [29].

B. Device Ecosystem and Integration

The device ecosystem for Private 5G is still developing. Many consumer devices do not natively support specific frequency bands, such as CBRS Band 48, or the necessary private network profiles without modifications. Additionally, integrating 5G with legacy municipal systems requires specialized protocol translation and considerable systems integration expertise, often relying on third-party managed service providers [30].

C. Privacy and Data Sovereignty

The deployment of dense sensor networks raises privacy concerns related to surveillance. While private networks enable cities to maintain data sovereignty by preventing data from passing through the public internet, aggregating data from cameras and sensors requires strong governance frameworks. Technologies like "Edge AI" help address this by processing data locally and discarding raw video feeds, transmitting only metadata (e.g., "traffic jam detected') [31] [32].

VI. CONCLUSION

Private Wireless Networks are becoming vital for the next stage of Smart City development. By leveraging shared spectrum and 5G technologies, cities can build "sovereign" infrastructure that outperforms traditional Wi-Fi and public cellular networks in terms of reliability, security, and long-term cost efficiency. Case studies from Sunderland, Las Vegas, Liverpool, Tucson, and Brownsville demonstrate that these networks are more than just experiments; they generate real ROI, from saving millions in operations to providing life-saving healthcare and enhancing public safety. However, progress relies on effective spectrum management and careful planning. As cities adopt "Neutral Host" models to lower capital costs and reduce technical complexity, combining Private 5G for essential outdoor mobility with Wi-Fi/LoRaWAN to support various use cases will shape the connected city of the future.

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