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Exploring the Potential of Private Wireless Networks for Enhanced Healthcare Services and Applications

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Abstract: The digitization of the healthcare sector, driven by the growth of the Internet of Medical Things (IoMT), remote telesurgery, and data-intensive diagnostic imaging, has revealed the limitations of older wireless technologies such as Wi-Fi. This paper offers a comprehensive technical analysis of Private Wireless Networks (PWN), focusing on Private 5G (P5G) and Private LTE, as essential enablers for the next generation of smart hospitals. It explores the shift from contention-based connectivity to deterministic cellular standards (3GPP Releases 16/17), highlighting the roles of Mobile Edge Computing (MEC) and Network Slicing in enabling Ultra-Reliable Low Latency Communications (URLLC). The paper reviews the regulatory spectrum environment by comparing the U.S. CBRS framework with international licensing models and provides a detailed performance comparison with Wi-Fi 6. Through case studies of the Cleveland Clinic, Veterans Affairs, and Region Stockholm, along with an in-depth economic analysis of Total Cost of Ownership (TCO), we demonstrate that although Private 5G involves higher initial costs, it offers superior security, reliability, and operational efficiency for mission-critical healthcare applications.

Keywords: Private 5G, Healthcare IoT, Network Slicing, Mobile Edge Computing, URLLC, Telesurgery, CBRS, Wi-Fi 6, Digital Twins, Medical Device Security.

I. INTRODUCTION

The modern healthcare ecosystem is undergoing a significant transformation driven by the "Fourth Industrial Revolution" (Industry 4.0), requiring a shift from fragmented, isolated information systems to fully integrated, real-time cyber-physical environments. Modern medical facilities increasingly depend on high-bandwidth, low-latency connectivity to support emerging technologies such as robotic telesurgery, augmented reality (AR) diagnostics, and large-scale remote patient monitoring (RPM) [1]. However, the current wireless standard, Wi-Fi (IEEE 802.11), has inherent limitations in reliability, mobility management, and security, making it inadequate for life-critical Operation Technology (OT) applications [3].

Private Wireless Networks (PWN), especially those based on 5G Standalone (SA) architecture, provide a deterministic alternative. Unlike public cellular networks, which share resources with the general public, private networks are dedicated to a specific enterprise, ensuring that critical medical telemetry is not affected by external network congestion [2]. The deployment of Private 5G is driven by specific Quality of Service (QoS) needs: Ultra-Reliable Low Latency Communications (URLLC) for haptic feedback in surgery; Massive Machine Type Communications (mMTC) for dense sensor networks; and Enhanced Mobile Broadband (eMBB) for volumetric imaging [2].

This paper examines the technical architecture, regulatory frameworks, and economic viability of Private 5G in healthcare. It investigates how enabling technologies such as Non-Orthogonal Multiple Access (NOMA) handle interference [3] and how Mobile Edge Computing (MEC) reduces latency for AI-driven diagnostics [2]. Additionally, it discusses the challenges of integrating legacy medical devices and the changing security landscape, offering a roadmap for healthcare administrators and network architects.

II. NETWORK ARCHITECTURE AND ENABLING TECHNOLOGIES

Implementing a private 5G network in a hospital setting requires a specialized architecture that differs significantly from commercial carrier deployments. It involves integrating cellular-grade infrastructure into the hospital's IT/OT perimeter.

A. 5G Standalone (SA) vs. Non-Standalone (NSA)

While early 5G deployments used Non-Standalone (NSA) architectures relying on 4G LTE control planes, the strict requirements of healthcare demand 5G Standalone (SA). 5G SA uses a Service-Based Architecture (SBA) in the core network, separating the control plane from the user plane.

- **User Plane Function (UPF):** In a private hospital setting, the UPF is hosted locally on-site. This ensures that sensitive Protected Health Information (PHI) is transmitted directly to the hospital's internal data center, bypassing the public internet and the mobile operator's core network, thereby maintaining data sovereignty and reducing latency [2].
- **Control Plane:** The Access and Mobility Management Function (AMF) and Session Management Function (SMF) manage device authentication and QoS policies. In 5G SA, these can be virtualized and run on standard servers, allowing flexible scaling [4].

B. Mobile Edge Computing (MEC) Integration

To achieve the sub-millisecond latencies promised by 5G, the physical distance between the radio and the compute resources must be minimized. Mobile Edge Computing (MEC) places computational power at the edge of the network, typically co-located with the Baseband Unit (BBU) in the hospital's server room.

- **Data Processing:** MEC enables real-time processing of high-bandwidth video streams from surgical cameras or patient monitoring systems. Instead of transmitting terabytes of raw data to a centralized cloud, the MEC processes data locally and sends only actionable insights or alerts to the central system [2].
- **ETSI Architecture:** The European Telecommunications Standards Institute (ETSI) defines an architecture in which MEC applications interact directly with the 5G User Plane, enabling dynamic traffic steering based on application needs [5].

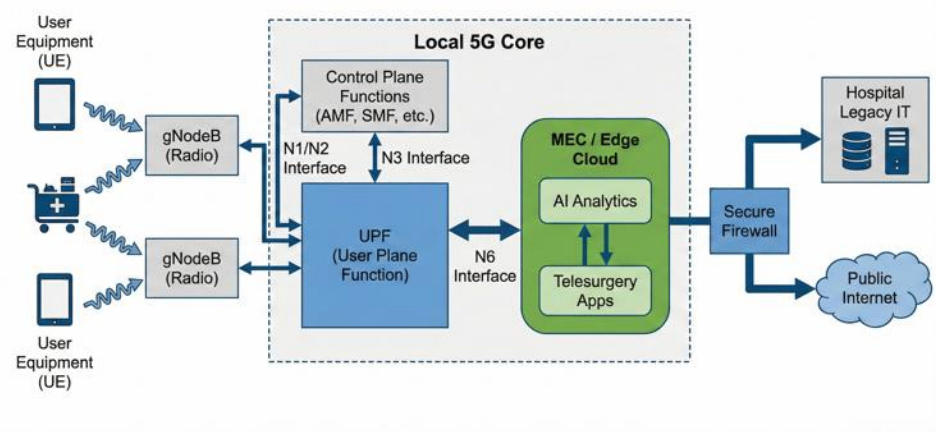

Figure 1: Private 5G System Architecture in a Healthcare Environment

C. Network Slicing and NOMA

Network slicing enables the physical network to be logically divided into separate virtual networks.

- **Isolation:** A hospital can set up a "Critical Care Slice" with dedicated resources for ventilators and cardiac monitors, separate from a "Guest Wi-Fi Slice" or a "Facilities Management Slice" for smart elevators. This isolation prevents traffic surges in one slice from affecting the performance of another [2].
- **NOMA:** To handle the high device density in a hospital (mMTC), Non-Orthogonal Multiple Access (NOMA) allows multiple users to share the same time and frequency resources by distinguishing them through power levels. This significantly improves spectral efficiency compared to Orthogonal Multiple Access (OMA) used in 4G, which is essential when thousands of sensors transmit simultaneously within a limited ward [3].

III. Spectrum and Regulatory Landscape

Access to radio spectrum is essential for private cellular networks. Unlike the unlicensed 2.4/5 GHz bands used by Wi-Fi, 5G requires managed spectrum to remain interference-free.

A. The CBRS Framework (United States)

In the United States, the Citizens Broadband Radio Service (CBRS) in the 3.5 GHz band (3550–3700 MHz) has democratized access to LTE and 5G spectrum through a three-tiered sharing model managed by a Spectrum Access System (SAS) [6].

Table 1: CBRS Spectrum Tiers and Healthcare Usage [6]

Tier	Access Type	Priority	Healthcare Application
Tier 1	Incumbent	Highest	**US Navy / Satellite:** Must be protected. Hospitals in coastal areas (within ~430km of DPA boundaries) may face dynamic channel reassignment [6].
Tier 2	Priority Access License (PAL)	Medium	**Critical Operations:** Hospitals purchase PAL licenses to guarantee interference-free spectrum for life-support systems and telesurgery [6].
Tier 3	General Authorized Access (GAA)	Lowest	**Non-Critical IT:** Used for staff voice communication, asset tracking, and guest services. Similar to Wi-Fi but with LTE range [7].

Operational Risks: Reliance on the cloud-based SAS presents a specific risk: if the network loses connection to the SAS for more than 240 seconds (the "Transmit Expire timer"), the radios must stop transmitting to protect incumbents. This "heartbeat" requirement calls for strong backhaul redundancy for hospitals using CBRS [8].

B. Global Spectrum Allocation

International regulators have adopted different models to support private networks, shaping the deployment strategies of global healthcare providers [9].

Table 2: Global Private 5G Spectrum Availability [9]

Country	Frequency Band	Licensing Model	Notes
United States	3.55–3.7 GHz (CBRS)	Dynamic Sharing (SAS)	Flexible but requires SAS connectivity.
Germany	3.7–3.8 GHz	Direct Local License	"Campus Networks" reserved for industry/enterprise.
United Kingdom	3.8–4.2 GHz	Shared Access License	Low cost, coordinated by Ofcom.
Japan	4.6–4.9 GHz, 28 GHz	Local 5G License	High frequency bands support high throughput for robotics.
Netherlands	3.5 GHz	Local Permit	Plot-based licensing valid until 2040.
France	2.6 GHz (TDD)	Vertical Spectrum	Targeted at industrial verticals.
Sweden	3.7 GHz, 26 GHz	Local Permits	Used in Region Stockholm healthcare projects.

IV. COMPARATIVE PERFORMANCE: PRIVATE 5G VS. WI-FI 6

While Wi-Fi 6 (802.11ax) introduces enhancements like OFDMA, Private 5G provides architectural benefits in determinism and mobility that are unmatched and better suited for OT workloads.

A. Determinism and Latency

The main difference is the access method. Wi-Fi uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), a "listen-before-talk" protocol. In crowded environments, this leads to unpredictable back-off times and increased latency (jitter). 5G uses a scheduled resource block system, where the network assigns exactly when each device transmits [7].

- **Empirical Evidence:** Studies comparing Wi-Fi 6 and 5G LANs in industrial environments show that while Wi-Fi 6 achieves low average latency, it exhibits "large tails" in the latency distribution (outliers) under load. 5G maintains bounded latency tails, ensuring that control packets for robots arrive within the safety threshold [10].
- **Packet Loss:** In high-interference scenarios, 5G shows significantly lower packet loss rates thanks to robust channel coding and Hybrid ARQ mechanisms, while Wi-Fi packet loss increases with user density [10].

B. Mobility and Coverage

- **Handover:** Wi-Fi roaming is controlled by the client; the device decides when to switch Access Points (APs), often sticking to a weak signal ("sticky client'), which can cause data interruptions. 5G handover is controlled by the network, enabling seamless transfers as a patient monitor moves between wards [10].
- **Coverage:** Because of higher transmit power and improved receiver sensitivity, a single 5G small cell can cover the same area as 3-4 Wi-Fi APs. This reduces the cabling infrastructure in ceilings, helping with infection control by reducing the need to open ceiling tiles [11].

Table 3: Technical Comparison of Wi-Fi 6 and Private 5G [10]

Feature	Wi-Fi 6 / 6E	Private 5G (SA)	Implication for Healthcare
Interference	Unlicensed (Shared)	Licensed / Protected	5G suitable for life-critical alarms.
Mobility	Break-before-make (Client decision)	Make-before-break (Network decision)	5G essential for mobile telemetry & AGVs.
Latency	10-20ms (High Jitter)	<10ms (Deterministic)	5G required for haptic telesurgery.
Security	WPA3 (Password/Cert)	SIM/eSIM (Hardware)	5G prevents device spoofing.
Density	~50-100 devices/AP	~10,000 devices/cell	5G enables massive sensor deployment.

V. CRITICAL USE CASES AND APPLICATIONS

Deploying Private 5G supports specific clinical workflows that were earlier limited by network constraints.

A. Telesurgery and Haptic Feedback

Remote robotic surgery requires the real-time transmission of stereoscopic video (from the patient to the surgeon) and haptic feedback signals (from the robot to the surgeon).

- **Latency Thresholds:** Research shows that total system latency must remain below 200–300 ms to avoid surgeon motion sickness and operational errors [2].
- **Network Requirements:** While video requires high bandwidth (15–20 Mbps), the haptic signal is low bandwidth but highly sensitive to jitter. 5G URLLC maintains network latency below 10ms with jitter below 1ms, leaving most of the latency budget for video processing [2]. A study on 5G telesurgery showed that latency stayed stable around 30ms, compared to 54ms on legacy networks, greatly enhancing surgical precision [12].

B. Digital Twins and Predictive Modeling

Digital twins create virtual models of patient physiology or hospital operations.

- **Living Heart Project:** This initiative leverages 5G to model human heart physiology, allowing surgeons to simulate procedures on a "digital heart" before performing surgery on a patient. The high data-transfer capacity of 5G is necessary to stream the large datasets generated by the simulation [13].
- **Rare Disease Modeling:** In Spinal Muscular Atrophy (SMA), digital twins model the distribution of gene therapy vectors (AAV), thereby lowering the need for invasive tests and decreasing the risk of adverse drug reactions by approximately 30–40% [14].

C. Massive Remote Patient Monitoring (RPM)

Private 5G expands the hospital's reach into the home ("Hospital at Home").

- **Scale and Power:** 5G’s mMTC capabilities support densities of up to 1 million devices per square kilometer [2].
- **Wearables:** New "RedCap" (Reduced Capability) 5G sensors operate on low power and continuously transmit vital signs without the frequent recharging required by Wi-Fi devices. This enables ongoing monitoring of chronic conditions without overburdening the patient [15].

D. Emergency Response and Drones

Region Stockholm’s 5G project uses the network to control drones that deliver Automated External Defibrillators (AEDs) to cardiac arrest scenes. The dedicated spectrum ensures that control signals are not lost, even if commercial networks become overloaded with public emergency calls. Additionally, ambulances transmit real-time video to emergency physicians, enabling pre-arrival diagnosis [16].

VI. SECURITY, PRIVACY AND COMPLIANCE

Security in healthcare is regulated by strict laws (such as HIPAA and GDPR) that ensure the confidentiality, integrity, and availability of Patient Health Information (PHI).

A. Intrinsic 5G Security Features

Private 5G offers a "Zero Trust" baseline:

- **SIM Authentication:** Mutual authentication ensures that only authorized devices gain access to the network. Hardware-based SIMs are much more difficult to clone than Wi-Fi credentials [11].
- **IMSI Encryption:** 5G introduces the Subscription Concealed Identifier (SUCI), which encrypts the user's permanent identity (IMSI) over the air. This prevents "Stingray" devices from tracking the location of medical staff or patients within the facility [11].

B. Network Isolation and Compliance

Network slicing offers strong isolation. A breach in the "Guest" slice cannot laterally spread to the "Surgical" slice because they are logically separated at the core network level. This feature helps ensure HIPAA compliance by strictly segregating PHI traffic and encrypting it [2]. However, administrators must stay alert against signaling attacks (GTP/Diameter manipulation) and should secure roaming interfaces if the private network interacts with public carriers [17].

C. Quantum Threats

As 5G networks are built for long-term lifecycles (10-15 years), the risk that quantum computing will compromise current encryption is a concern. Forward-thinking deployments are beginning to explore quantum-resistant encryption methods for the 5G backhaul to protect sensitive genomic data that retains value for decades [18].

VII. ECONOMIC ANALYSIS AND FEASIBILITY

The adoption of Private 5G represents a shift from Operating Expenditure (OPEX) models, where companies pay a carrier, to Capital Expenditure (CAPEX) models, where companies own the infrastructure. However, hybrid models are also available.

A. Cost Structure

- **CAPEX:** Includes the purchase of Small Cells (gNBs), Core Network software licenses, and MEC servers.
- **OPEX:** Includes spectrum access fees, maintenance, and energy consumption.
- **TCO Savings:** Despite the high upfront costs, a University of Bristol study shows that Private 5G can reduce Total Cost of Ownership (TCO) by up to 53% over time. These savings come from integrating multiple networks—Wi-Fi for data, DECT for voice, and proprietary pager networks into a single, unified 5G platform [19].

B. Rural vs. Urban Deployment

Economic modeling indicates that in rural areas with low population density, the "Infrastructure Provider" (InP) model—where a third party builds the network, and multiple hospitals or clinics share it—reduces CAPEX barriers. In dense urban areas, the high demand for data makes standalone enterprise ownership more financially viable [19].

VIII. CASE STUDIES

A. Cleveland Clinic (USA)

Cleveland Clinic's Mentor Hospital in Ohio represents a pioneering "greenfield" deployment where Private 5G was integrated during construction. The network, built with Verizon, supports patient check-in kiosks, digital infotainment systems, and AR/VR training tools. This deployment emphasizes the "hybrid" strategy, with 5G managing critical clinical workflows and Wi-Fi handling general IT needs [20].

B. VA Palo Alto Health Care System (USA)

The U.S. Department of Veterans Affairs tested a 5G network to support AR-assisted presurgical guidance. The network's low latency enables surgeons to view 3D holographic X-rays overlaid on the patient in real time, enhancing surgical planning and reducing procedure time [21].

C. Region Stockholm (Sweden)

Supported by an €8.5 million budget, this project integrates Private 5G into the pre-hospital care network. The system enhances the "situational awareness" of dispatchers by streaming video from ambulances and manages the flight paths of medical drones, showcasing the value of wide-area private networking beyond hospital walls [22].

IX. CHALLENGES AND FUTURE DIRECTIONS

Despite the clear benefits, significant hurdles remain for widespread adoption.

- **Device Ecosystem:** Native 5G medical devices are currently in limited supply. Hospitals often depend on 5G-to-Wi-Fi gateways to connect legacy MRI machines and pumps, which increases complexity and costs [2].
- **Complexity:** Managing a 5G network is more complex than managing a Wi-Fi network. It requires specialized telecommunications expertise that most hospital IT departments lack, creating a need for managed service providers [19].
- **Interference Management:** In CBRS deployments, careful planning and geographic risk assessment are crucial to reduce the risk of outages caused by incumbent Navy radar activity (in Tier 3/GAA) that affects spectrum access [6].

X. CONCLUSION

Private Wireless Networks represent a crucial shift in healthcare infrastructure, moving from "best-effort" connectivity to "mission-critical" reliability. Evidence shows that Private 5G, enabled by Standalone architecture, MEC, and Network Slicing, outperforms Wi-Fi 6 in key aspects such as latency, reliability, and security, which are essential in modern medicine. Although high initial CAPEX and a developing device ecosystem pose implementation challenges, the potential for long-term TCO savings and support for life-saving technologies like telesurgery and real-time AI diagnostics make Private 5G an essential component of future smart hospitals. As regulations such as CBRS 2.0 advance and device ecosystems grow, Private 5G is set to become central to healthcare delivery.

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