Private Network - *Anywhere and Everywhere*

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***Abstract*—Cellular service providers aim for widespread coverage in the U.S., yet many indoor and rural areas face coverage gaps due to limited infrastructure. Service quality has reportedly worsened in recent years. To address this, the FCC introduced the CBRS spectrum to enhance enterprise applications and rural internet access. This study explores private network deployment using backhaul technologies such as Mobile Network Operators (MNOs), Wired ISPs, and Satellite Communications (e.g., Starlink). These technologies are critical for essential applications like disaster response and military operations, as well as commercial uses such as smart agriculture. The research evaluates private network performance by analyzing throughput and latency across these backhaul options.**

I. Introduction

With the escalating need for wireless services, there is an increasing demand for connectivity in all locations. The United States encompasses a vast land area, predominantly rural, where agricultural zones and rural residences are in dire need of wireless services. The challenge lies in the deployment of connectivity by Macro operators, such as Mobile Network Operators (MNOs), due to the substantial investment and deployment requirements for base stations. Additionally, the necessity of laying fiber and supplying power for this infrastructure incurs significant capital and operational expenses. For Wi-Fi services, establishing backhaul connections (like those provided by Xfinity and Comcast) requires integration into building infrastructure. In mountainous areas, where there may be only a few homes, the extensive costs of infrastructure development are not justifiable.

In rural regions, basic wireless connectivity remains a significant challenge [1], making the adoption of advanced technologies like 5G even more difficult. Implementing Industry 4.0 solutions such as smart agriculture and smart grids in these areas is often unfeasible, especially in locations at the edge of MNO coverage with RSRP levels greater than -118 dBm. This leads to poor downlink and uplink performance, resulting in user frustration.

Additionally, providing reliable indoor cellular service with outdoor macro base stations is problematic, even in urban and suburban areas, particularly with 5G, due to higher frequency bands and energy-efficient buildings with e-rated windows [2]. To address these challenges, the US FCC introduced the Citizens Broadband Radio Service (CBRS) in the 3.5 to 3.7 GHz range in 2019. This mid-band spectrum offers an ideal balance between range and data throughput, supporting 4G-LTE and 5G-NR technologies. The adoption of CBRS has accelerated private network deployments in various environments, including warehouses, logistics centers, and educational institutions. Furthermore, CBRS technology extends coverage at the fringes of public MNO networks, linking CBRS Access Points and the core network to MNOs for enhanced indoor and outdoor services.

Additionally, in situations where public MNO signal strength are weak due to coverage gaps or limited base station deployment, alternative backhaul options like satellite communications, for instance, Star-link, become viable. This enables the establishment of private networks in virtually any location. This study explores various scenarios where private networks can be rapidly deployed, typically in a matter of hours.

Our proposed ”mobile” private networks offer a versatile and robust solution for a wide array of critical use cases, particularly in environments where connectivity is not just a convenience, but a necessity. Private networks offer localized control, enhanced security through dedicated spectrum, and independence from public network infrastructure, making them ideal for critical applications. These networks can make a life-saving difference or significantly enhance operational efficiency in various scenarios. In our study, we employed a setup utilizing the CBRS managed by MNOs through a Spectrum Access System (SAS). This setup ensures continuous operation by maintaining a heartbeat signal to a centralized system, even in the face of intermittent WAN connectivity. With the SAS heartbeat timeout extended from 4 minutes to 6 hours, our approach allows the network to function locally, much like a LAN, with minimal dependence on high-speed internet. This configuration prioritizes connectivity across devices within the same network, with the internet primarily facilitating essential communication between the CBRS and the centralized database. The contributions of this paper include:

- The first dynamic deployment of a private network enabled by three different technologies (MNO, ISP and Satellite).
- A comprehensive comparison of these technologies in terms of uplink, downlink, and latency performance.
- A scalable framework that can be extended for real-world use cases.

II. Spectrum Characteristics

A. 5G Spectrum Capabilities

The operational spectrum for 5G services is segmented into three distinct bands, each tailored for specific use cases and performance attributes. Utilizing the full spectrum enables

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enterprises to tailor their network traffic based on the transmission's environment and distance. 5G's peak performance is achieved through the utilization of high frequencies in the millimeter-wave band. However, due to the limited range of higher frequencies, 5G employs a combination of frequency bands for widespread application.

1) Low Band: The low-band spectrum of 5G is engineered to deliver extensive, long-range coverage. Serving as the foundational layer of 5G, it spans vast areas, covering hundreds of square miles, and operates in the 600–850 MHz spectrum. Although the low band's throughput or performance is less compared to the mid and high bands, it excels in range. The speeds in this band is very limited with a range from 50–250 Mbps per base stations which would be shared across many mobile devices connecting to that base station. So low-band deployments is really not a very attractive solution to provide enough capacity.

2) Mid Band: The mid band in 5G is optimized for a harmonious balance between speed and coverage, making it ideal for urban, suburban, and small city environments. Operating in the 2.5–4.2 GHz range of the 5G spectrum, the mid band is capable of delivering functional speeds that vary from 100–900 Mbps for an individual wireless client. Its versatility and the possibility for private spectrum utilization make the mid band a preferred choice for many businesses and enterprises.

3) High-Band: High-band 5G operates on the millimeter-wave spectrum, utilizing frequencies between 25–39 GHz. This band is characterized by its exceptionally high speeds, which can reach up to 3 Gbps, making it the fastest segment of the 5G spectrum. However, its range is comparatively short, extending at most to 1,500 feet with a line-of-sight from a small cell tower. In practical deployments actual vegetation or buildings reduce the coverage range to much smaller range. In densely populated urban areas, high-band 5G is employed to accommodate the high demand from large populations where mostly line-of-sight coverage is possible (e.g., stadiums).

B. Spectrum in Enterprise Deployment

Mobile operators have rapidly engaged in acquiring access to 5G spectrum. The FCC regularly conducts auctions, allowing entities to bid for sections of the 5G spectrum in the low, mid, and high bands. This process opens a plethora of possibilities for both consumers and businesses to embrace private 5G networks and encourage widespread adoption.

Enterprises now have the capability to utilize the 5G spectrum for launching high-speed, low-latency services. A significant development is the opportunity for businesses to establish their own private 5G networks using private spectrum options, such as the CBRS band in the USA. Leveraging the CBRS band for 5G LAN solutions [3], enterprises can maintain control over their data and reduce dependence on commercial infrastructure that relies on public spectrum, which often involves costly contracts with per-device fees.

The CBRS spectrum is managed through a tiered system, encompassing a 150 MHz band ranging from 3.55 GHz to 3.7 GHz [4]. Originally allocated for naval use, the FCC [5] has now made a segment of this spectrum available for private deployment, heralding opportunities akin to the early internet era. This enables businesses to develop and offer products and services utilizing this novel technology.

The FCC safeguards this mid-band spectrum through tiered access and advanced radio-monitoring technologies [6] [7]. The CBRS spectrum is categorized into three distinct tiers: Incumbents, Priority Access License (PAL [8]), and General Authorized Access (GAA). Organizations can utilize the CBRS band by obtaining licensed access to the Spectrum Access System (SAS), enabling them to construct and manage their own 5G networks, independent of public carriers. Employing FCC-certified equipment, businesses can establish 5G networks that offer comprehensive coverage for facilities like enterprise buildings, warehouses, and educational campuses.

Private spectrum options, such as CBRS in the United States, allow the deployment of mobile services without disrupting existing systems like Wi-Fi. This capability facilitates the smooth implementation of digital strategies on a dedicated wireless channel. It also supports private 5G wireless networks essential for applications requiring uninterrupted connectivity, adherence to strict service level agreements (SLA), and consistent service availability.

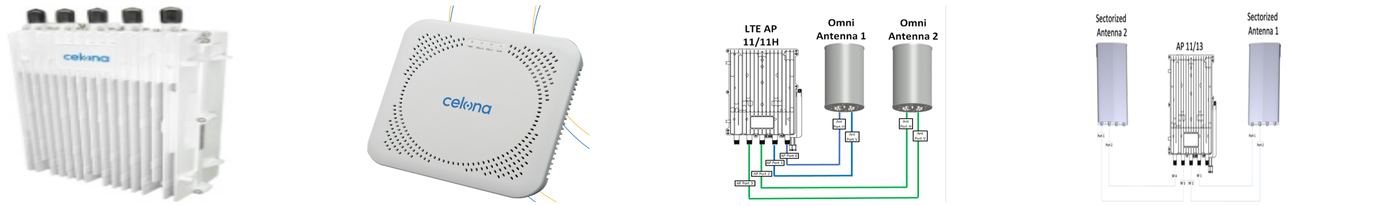
III. Advantages of Private Networks

Private networks offer significant advantages for businesses, primarily due to their independence from mainstream mobile operators, such as Verizon and AT&T. This autonomy allows companies to manage data consumption, network presence, and device prioritization, resulting in reduced bandwidth costs. Furthermore, private networks can be specifically tailored to meet the unique needs of an enterprise, providing levels of performance, security, and reliability that public networks cannot match. Enhanced security is achieved through the use of SIM technology and encryption, ensuring that sensitive data remains within the enterprise. Additionally, private networks offer improved dependability with consistent low latency and extended coverage, outperforming Wi-Fi in both indoor and outdoor environments.

With the introduction of spectrum-sharing frameworks like CBRS in the USA, private networks now enjoy dedicated communication bands, free from external interference—a common issue with Wi-Fi. The extended coverage capabilities of private networks, offering up to ten times the outdoor and quadruple the indoor reach compared to Wi-Fi, further highlight their superiority. Understanding these benefits is crucial for businesses considering private networks, as these advantages are facilitated by specialized hardware like Access Points (APs) connected to antennas, which are essential for maximizing network performance (Fig. 1 a, b c, and d).

IV. Critical Use Cases for Private Networks

Our proposed "mobile" private networks offer a versatile and robust solution for a wide array of critical use cases,



(a) Outdoor AP *(b) Indoor AP* *(c) AP with Omni* *(d) AP with Sector*

Fig. 1: *Outdoor and Indoor AP with Omni and Sector Antenna Connections*

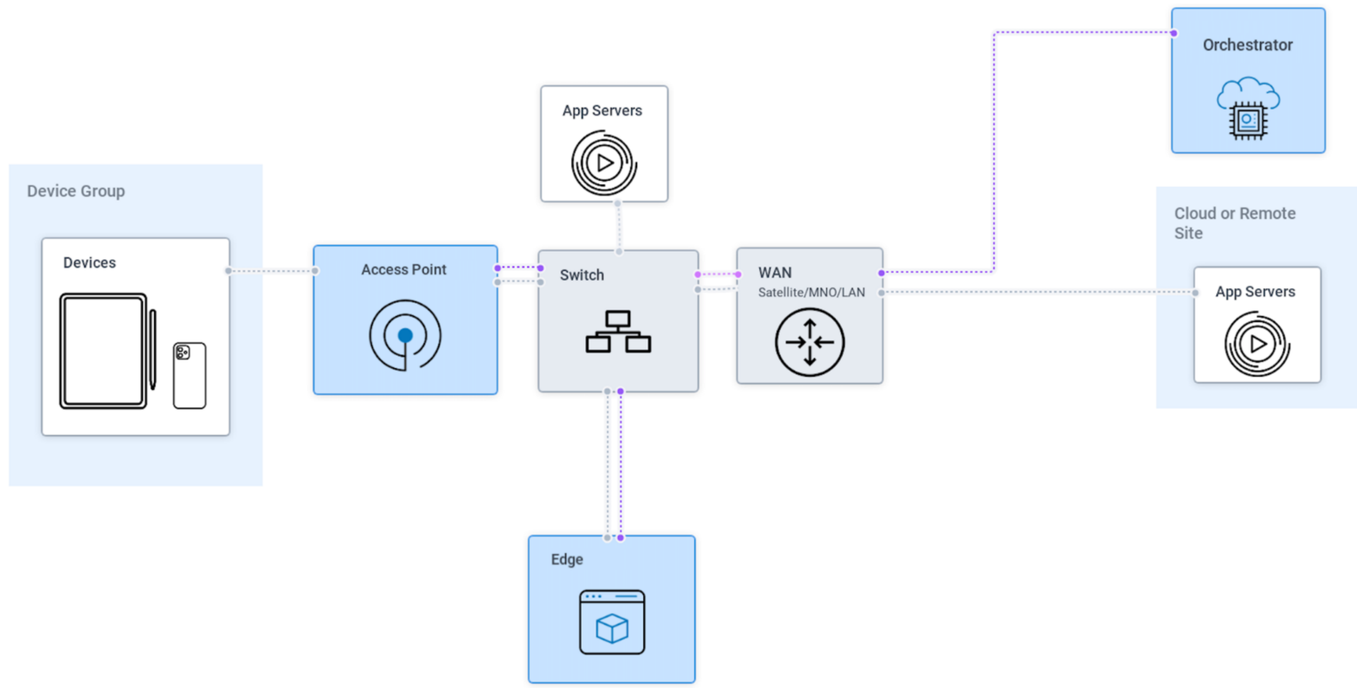


Fig. 2: 5G LAN End to End Architecture using WAN as a Backhaul Connection.

particularly in environments where connectivity is not just a convenience, but a necessity. As illustrated in Figure 3, these networks can make a life-saving difference or significantly enhance operational efficiency in various scenarios. Below, we discuss these critical scenarios in detail.

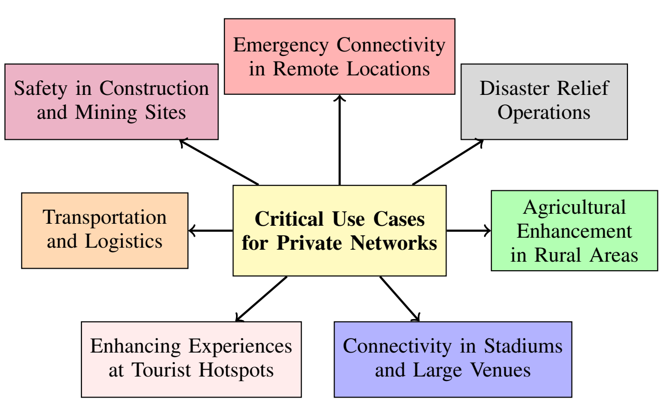


Fig. 3: Critical Use Cases for Private Networks

A. Enabling Emergency Connectivity in Remote and Hazardous Locations

In remote and hazardous areas like Lake Tahoe, Mount Everest, and the Grand Canyon, where traditional communication networks are often absent, deploying private networks using satellite backhaul, such as Starlink, ensures critical connectivity. This setup leverages low-Earth orbit satellites to maintain a robust link between on-site devices and emergency services. By establishing a private network with an Omni antenna connected to a satellite-enabled Access Point (AP) and core network, real-time GPS tracking and communication become possible, significantly enhancing response times during emergencies.

B. Agricultural Enhancement in Rural and Isolated Areas

In rural and isolated agricultural regions, private networks can be implemented using CBRS spectrum with either MNO or satellite backhaul. This approach supports the deployment of precision farming technologies, including real-time soil and crop monitoring, automated irrigation systems, and dronebased surveillance. By connecting the CBRS-enabled APs to a robust backhaul like Starlink or a local MNO, farmers gain reliable, high-speed connectivity, ensuring that modern agricultural practices can be carried out effectively even in areas with limited public network access.

C. Enhancing Connectivity in Stadiums and Large Event Venues

Large venues like stadiums, arenas, and convention centers demand high-capacity, low-latency connectivity to manage the vast number of users and services. Deploying private networks with a wired ISP or MNO backhaul in these settings ensures seamless communication. By connecting the APs to a reliable backhaul and using the Edge OS for QoS management, these networks support real-time video streaming, secure financial transactions, and efficient crowd management, catering to thousands of attendees with consistent service quality.

D. Revolutionizing Transportation and Logistics

In the transportation and logistics sectors, private networks are crucial for real-time tracking and management of vehicles, cargo, and passengers across extensive and often remote areas. These networks can be established using MNO or satellite backhaul, connecting the network's APs to the Edge OS, which manages traffic prioritization and network performance. This setup enables continuous communication between vehicles and control centers, facilitating optimized route planning, timely maintenance, and enhanced safety, all while maintaining reliable connectivity across vast distances.

E. Ensuring Safety and Efficiency in Construction and Mining Sites

Construction and mining sites, typically located in remote areas with minimal existing infrastructure, benefit greatly from private networks with satellite or MNO backhaul. By deploying APs connected to a reliable backhaul and integrated with the Edge OS, these networks support the operation of heavy machinery via remote controls, real-time health and safety monitoring, and immediate access to emergency services. This configuration ensures seamless connectivity, allowing site managers to maintain constant oversight and enhance operational productivity and safety.

F. Supporting Disaster Relief and Emergency Response Operations

In disaster relief scenarios, where rapid deployment and reliable communication are critical, private networks enabled by satellite or MNO backhaul provide essential infrastructure. These networks, set up using portable APs and connected to the Edge OS, support real-time mapping of affected areas, coordination among various relief agencies, and efficient management of supply chains. By ensuring robust communication in disaster-stricken areas, these private networks significantly enhance the effectiveness and speed of relief operations, ultimately aiding in the swift recovery of affected regions.

G. Enhancing Experiences at Tourist Hotspots

Tourist hotspots, especially those in remote or ecologically sensitive areas like national parks, historical sites, and remote islands, require reliable connectivity to enhance visitor experiences. Private networks in these locations can be established using satellite or MNO backhaul, with APs strategically placed to cover critical areas. These networks enable real-time access to information, safety monitoring, and emergency services. By integrating these private networks with the Edge OS, site managers can ensure that visitors have access to consistent connectivity, improving their overall experience while maintaining the site's safety and operational efficiency.

V. Architecture and Deployment Scenarios of Private Networks

The Edge or Core Network OS is a robust, scalable cloud-native operating system designed to provide continuous data plane, control plane, and spectrum management services for private cellular networks. Tailored for enterprise-level deployment, the Edge OS integrates 4G/5G core services for cellular packet transmission with a comprehensive IP stack, ensuring seamless integration with enterprise LANs. This system powers Edge Node appliances, assembled into a three-node Edge Cluster to guarantee high availability and fail-safe operations of private 5G networks.

Figure 4 illustrates the full architecture, extending from the device to the edge and orchestrator. Grey connections represent wireless links, while purple connections denote wired connections. This setup is crucial for ensuring Quality of Service (QoS) based on device grouping and effective spectrum management for channel allocation. Depending on the chosen Wireless Access Network (WAN) backhaul type—MNO, Wired ISP, or Satellite—this architecture allows the CBSD or Access Point (AP) to synchronize with the Spectrum Access System (SAS), acting as the registration and access point for spectrum authorization.

A. QoS Assurance and Spectrum Management

The Edge OS manages application-level QoS through MicroSlices, configured in the Orchestrator and enforced in the Edge Cluster. MicroSlices dynamically identify each critical application flow in the cellular network, assigning specific QoS Classes (QCI/5QI) that dictate traffic priority and network latency. As traffic transitions from the cellular network to the enterprise L2/L3 network, QoS settings from the Edge QCI are mapped to traditional QoS configurations, maintaining consistent service quality.

Spectrum optimization in private 5G networks is fully automated using advanced intelligent spectrum management algorithms within the Edge OS [9]. These algorithms enhance coverage and capacity by continuously monitoring and adaptively adjusting spectrum channels in response to detected interference or incumbent operations, particularly in CBRS environments. Intelligent Spectrum Management is compatible with shared, private licensed, or unlicensed spectrum models and includes Domain Proxy features for CBRS setups [4].

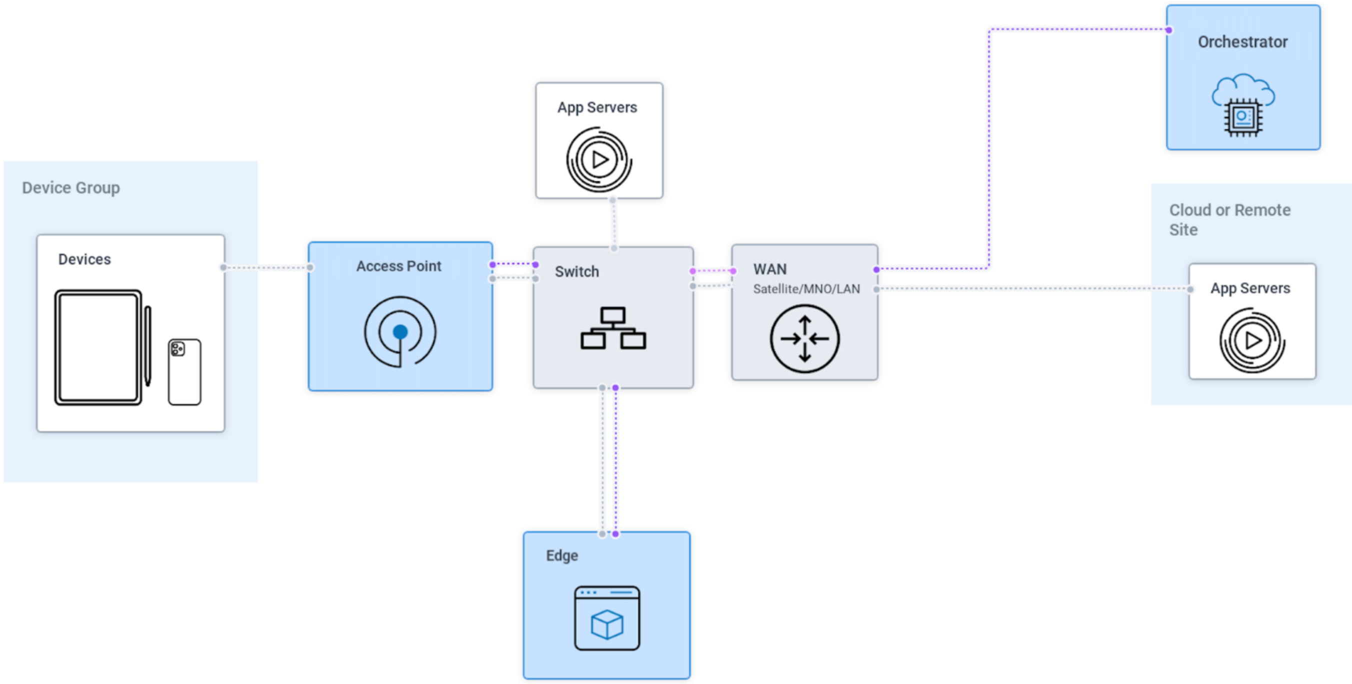


Fig. 4: 5G LAN End to End Architecture using WAN as a Backhaul Connection.

B. Deployment Scenarios

This architecture supports three primary backhaul connection scenarios to facilitate private networks anywhere: Satellite (e.g., Starlink, Viasat, HughesNet), Mobile Network Operators (MNOs), and Wired Internet Service Providers (ISPs). Operating on the CBRS spectrum (3.5 to 3.7 GHz) with 15 channels of 10 MHz each, these deployments utilize a Self-Optimizing Network (SON) algorithm for spectrum allocation, channel selection, power management, and Physical Cell ID (PCI) configuration.

1) Satellite Backhaul Connection: Satellite-based wireless broadband services, such as Starlink's "Portability," enable users to maintain their service address while connecting from any supported location within their continent. This feature facilitates private network coverage in areas with an unobstructed sky view. Satellite backhaul services offer Ethernet adapters for direct connections between private Edge infrastructure and satellite providers, eliminating the need for WAN links over Wi-Fi bridges. Low-earth orbit satellites provide reduced latency compared to traditional satellite WAN solutions, making them ideal for temporary work sites and rural locations lacking robust internet connections.

2) MNO as a Backhaul Connection: Major US operators like AT&T, TMO, and Verizon offer extensive 4G and 5G coverage across low, mid, and high spectrum bands, with RSRP signal strengths ranging from -65 to -120 dBm. However, indoor penetration remains challenging due to factors like outdoor macro base stations and e-glass layers in modern buildings. Private networks utilizing the CBRS spectrum with MNO backhaul can enhance connectivity in both indoor and fringe outdoor areas, as depicted in Figures 6 and 7.

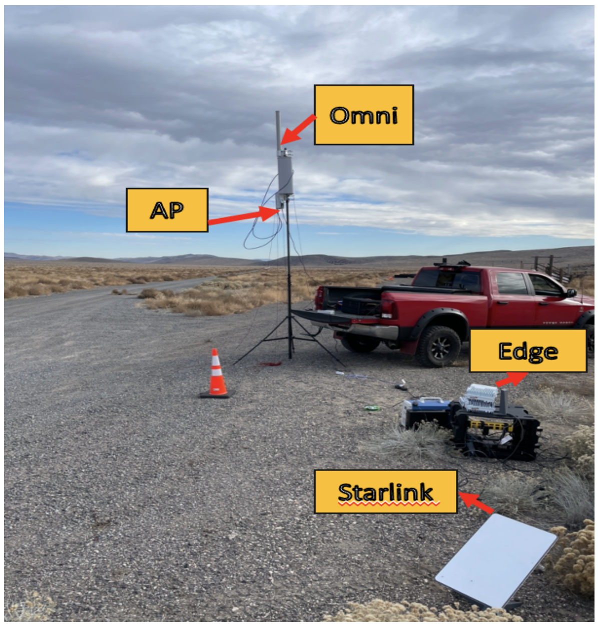


Fig. 5: Private Network Setup of Omni Antenna with Starlink as WAN.

3) Utilizing Wired ISP for Backhaul: In residential settings with congested Wi-Fi channels, leveraging existing wired ISP connections as backhaul can establish reliable private networks. This approach mitigates performance issues during peak usage of bandwidth-intensive applications like Zoom or live streaming, as shown in Figure 8.

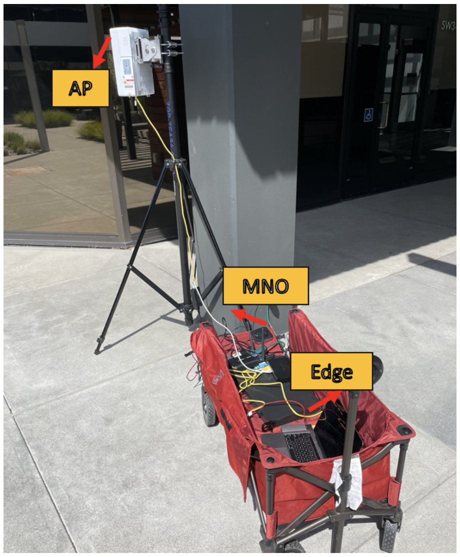


Fig. 6: Outdoor Private Network with MNO as WAN.

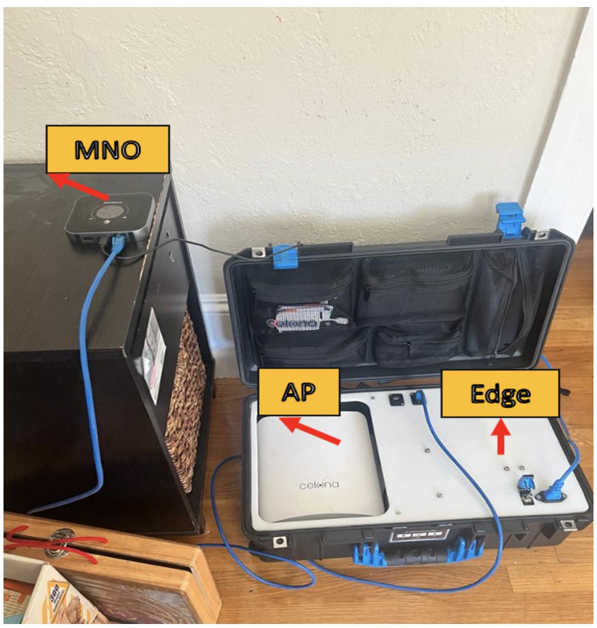


Fig. 7: Indoor Private Network with MNO as WAN.

4) Technical Challenges and Innovations: Building a mobile private network presents several technical challenges, including spectrum management, ensuring QoS, and maintaining connectivity across diverse environments. The Edge OS addresses these by automating spectrum optimization and dynamically managing QoS through MicroSlices. Scalability is achieved through the three-node Edge Cluster, ensuring high availability and fail-safe operations. The integration of SON algorithms for spectrum and resource management further enhances the network's adaptability and performance, representing a significant technical innovation in private network deployments.

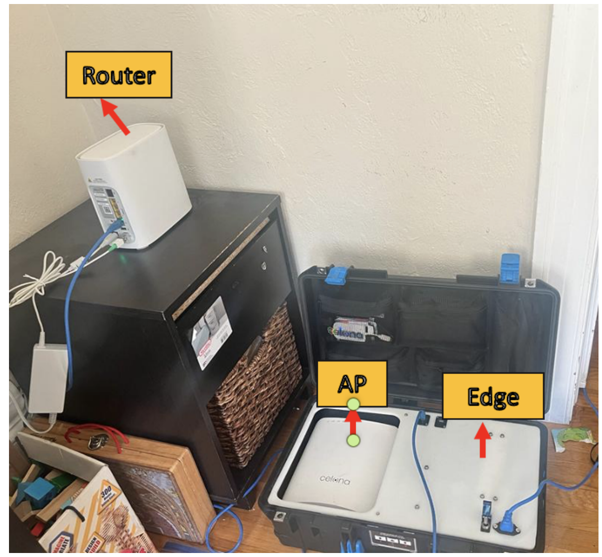


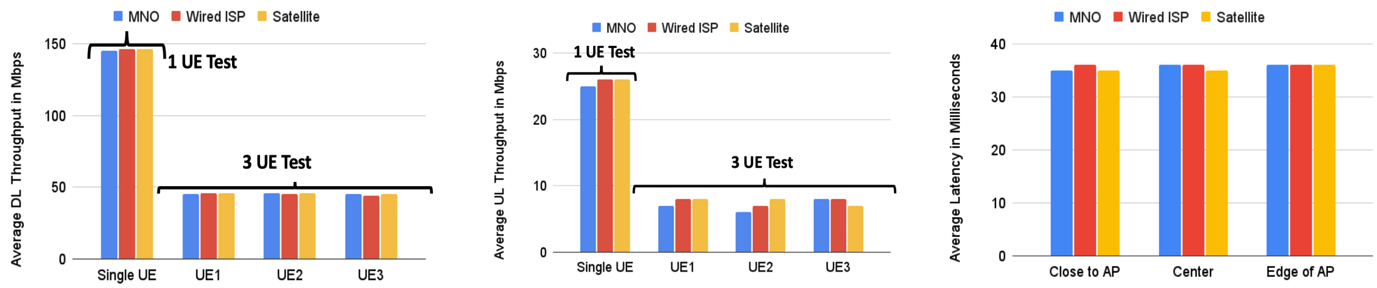
Fig. 8: Indoor Private Network with Wired ISP as WAN.

5) Scalability Considerations: Scalability issues are addressed by the cloud-native architecture of the Edge OS, which allows for seamless expansion of network nodes and efficient management of increasing device densities. The automated spectrum management and QoS assurance mechanisms ensure that the network can adapt to growing demands without compromising performance, making the framework suitable for large-scale real-world applications.

C. Performance Evaluation

This section assesses the performance of private networks using three different backhaul methods: Mobile Network Operators (MNOs), Wired Internet Service Providers (ISPs), and Satellite Communications (e.g., Starlink). The evaluation focuses on key metrics such as throughput and latency to determine the efficiency of each backhaul option in various scenarios, including military operations, disaster response, agriculture, and sports arenas.

1) Setup and Methodology: In our experimental setup, the CBRS Access Point (AP) was configured with a 20 MHz bandwidth, enabling carrier aggregation with two sectors using an omni antenna, effectively yielding a total bandwidth of 40 MHz. An iperf server was deployed on the core network or Edge, and a Google Pixel smartphone served as the iperf client to measure both downlink and uplink throughput. For latency measurements, the network IP address on the Edge was pinged to minimize delays introduced by other internet routers and switches. Most data within the private network remains local, requiring only a basic internet connection for communication between the CBRS AP and the Spectrum Access System (SAS) for spectrum registration and authorization. The objective of the experiment was to evaluate the efficiency of private networks across diverse backhaul technologies in environments where connectivity requirements can vary significantly.



(a) Avg. Downlink Throughput *(b) Average Uplink Throughput* *(c) Average Latency*

Fig. 9: *Performance Metrics Comparison of MNO, Wired ISP, and Satellite as Backhaul Connection to Enable Private Network*

2) Throughput Analysis: Figure 9(a) presents the average downlink throughput for each backhaul method. Initial tests conducted with a single User Equipment (UE) showed that the optimal downlink throughput in a 40 MHz bandwidth reached up to 146 Mbps in an uplink-heavy Time Division Duplexing (TDD) configuration. As depicted in Figure 9(a), introducing three additional Google Pixel UEs demonstrated fair distribution of resources among the UEs within the TDD slot-based system. Figure 9(b) illustrates the average uplink throughput performance, which starts at 25 Mbps for a single UE and adjusts dynamically as more UEs are added to the network.

3) Latency Analysis: Mission-critical applications often operate near the network's edge, necessitating low latency for reliable performance. This part of the study evaluated latency across three different UE connection setups: near the AP, at the center, and at the AP's edge, each with varying Reference Signal Received Power (RSRP) levels. Figure 9(c) displays the average latency, measured in milliseconds, for each backhaul connection type. The results indicate that latency remains around 35 milliseconds across all setups, demonstrating reliable performance suitable for critical applications in diverse environments such as mountainous regions, maritime areas, and forested locations.

VI. Conclusion

Universal wireless connectivity is essential, particularly in developed nations like the United States, where many indoor and rural areas still experience coverage gaps. This paper explores strategies for deploying private networks to address both critical and commercial needs by leveraging various backhaul technologies, including Mobile Network Operators (MNOs), Wired Internet Service Providers (ISPs), and Satellite Communications (e.g., Starlink). Utilizing the CBRS spectrum, we demonstrated enhanced coverage, security, and operational flexibility, ensuring reliable performance with average latency around 35 milliseconds.

Our performance evaluation indicated that each backhaul option offers distinct advantages in throughput and latency, making them suitable for diverse applications such as disaster response, military operations, and smart agriculture. Extending the SAS heartbeat timeout allowed the network to maintain local operations with minimal dependence on high-speed internet, ensuring continuous service even in areas with intermittent WAN connectivity.

Future work will focus on deploying these private network solutions in rural environments, integrating them with edge computing and Internet of Things (IoT) devices. Additionally, we aim to develop advanced Quality of Service (QoS) management techniques and hybrid network models to facilitate seamless transitions between private and public networks, thereby ensuring consistent and reliable connectivity for a wide range of applications.

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