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Private 5G NR Networks: Analytical Framework for Radio Interface Delays in Industrial Deployments

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***Abstract*— Private 5G networks, also referred to as Captive Non-Public Networks (CNPNs), are increasingly deployed to support latency-critical and heterogeneous services in industrial and campus environments. Maintaining a wireless network in scenarios of refineries, open and underground mines and ports is one of the major challenges that system integrators and network engineers face. Equipment is large, on the move and never in line of sight to other network devices.**

***Mining operations are dusty, loud and in challenging environments that take a toll on wireless equipment. After a significant investment in a wireless network, many face frustration with deficiencies in network uptime and durability. Accurate evaluation of processing latency in such networks requires transparent and traceable modeling of individual latency components across protocol layers. This paper presents a component-based latency analysis framework for 5G New Radio (NR) downlink transmissions, specifically tailored to CNPN scenarios.**

The proposed methodology decomposes latency into traffic generation, MAC layer queueing and scheduling, physical layer processing and transmission components. Traffic arrivals are modeled using periodic, aperiodic and mixed generation processes to reflect realistic private network workloads. Downlink scheduling is performed using deterministic, rule-based policies to ensure reproducibility and analytical clarity. Physical layer latency is evaluated based on NR numerology, bandwidth, modulation and coding schemes and retransmission behavior. The component-wise decomposition enables clear identification of latency bottlenecks and provides valuable insights for the design and dimensioning of latency-sensitive CNPN deployments.

***Keywords*— 5G NR, CNPN, URLLC, Scheduling, Radio resource blocks, Latency.**

I. INTRODUCTION

5G Captive Non-Public Network (CNPN) is a new wave in secured wireless data networking. A Private Cellular Network is basically a local area network (LAN) that uses cellular technologies (5G) to create a dedicated network which gives unified connectivity, optimized services and secure communication within a limited geographic area. 5G CNPN is suitable for industries that require extreme data security and low latency features [14].

Third generation Partnership Project **(3GPP)** Release 15 (2018–2019) marked the formal introduction of 5G NR (New Radio) and established the foundation for enhanced Mobile Broadband (eMBB) and ultra-reliable low-latency communication (URLLC) use cases. It defined the concepts of flexible numerology (sub-carrier spacing scaling with μ=0-4), frame structure and PHY/MAC procedures for scalable latency and bandwidth adaptation.

3GPP Release 16 (2020–2021) extended 5G from consumer broadband to industrial and mission-critical applications [3]. It added advanced URLLC enhancements, time-sensitive network (TSN) integration and enhanced positioning / sidelink features (V2X – Vehicle to Everything) for factory automation, autonomous transport, and private networks. [1].

5G NR is well suited for private deployments due to support for URLLC, standalone operation with local core, network slicing with guaranteed QoS, high device density and strong security. Private 5G NR networks are increasingly being deployed for mission-critical industrial applications such as mining, manufacturing, logistics and utilities. These environments demand low and predictable latency to support use cases like autonomous vehicles, real-time sensor control and remote machinery operation.

Critical KPIs for industrial private 5G include deterministic latency, reliability (PDR/BLER), resource utilization efficiency, availability and energy consumption. These directly impact mission-critical automation and control applications.

II. RESEARCH MOTIVATION AND OBJECTIVES

3GPP provides general latency guidelines, but most of the existing models are often public-network oriented; ignoring the unique features of non-captive private networks like Dedicated spectrum allocation, Stable UE populations, Configurable radio resource partitioning and High reliability and isolation from public traffic.

To design and optimize these networks, there is a need for practical and accurate latency models which will capture the individual components. In a private 5G context - latency contributors to Radio Interface Delay extend from UE scheduling to control channel access. A typical 5G private site deployment is shown in Fig. 1.

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3Ws of 5G CNPN

WHAT - Local Area Network (LAN) uses 5G wireless technology to create a customized secured unified connectivity within a geographic area.

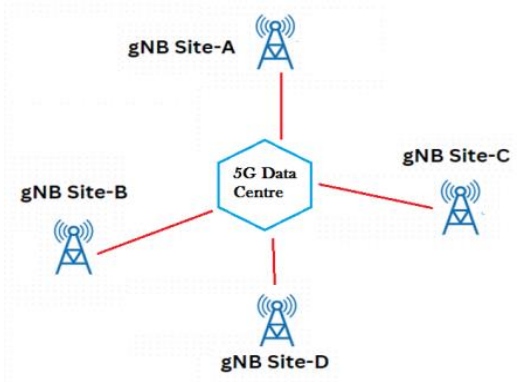


Figure 1. Stand-alone Non-Public Network with 04 gNodeBs

WHY - Feeble Public Network footprint areas, Industries needing high upload Throughput (HD Cameras), Low latency application area, High security operations, Client customization of mobile Network, Telecom Service Providers (TSPs) uninterested to expand network due to low ROI (Return on Investment).

WHERE - Mines, Refineries, Defense, Power, Sea Port, Airport, Research unit, Factories, Manufacturing sectors.

Existing Latency Models and Deployments

Existing latency models defined by 3GPP, ITU, and IEEE provide frameworks for understanding end-to-end delay in 5G and beyond. 3GPP TR 38.913 [4] and TS 23.501 [1] decompose latency into radio, core and transport segments, emphasizing components such as scheduling delay, HARQ, and user-plane processing. ITU-T Y.1541 [6] categorizes latency classes for different service levels (e.g., conversational, streaming, background) and set performance objectives for each. IEEE 802.1 TSN standards [7] define deterministic networking mechanisms for bounded latency in industrial Ethernet and 5G integration. Together, these models establish the analytical basis for latency simulation in both public and private 5G systems.

While the public 5G rollout in India has been rapid, the CNPN services, as in Fig. 2, are still in a nascent stage [9]. The public sector telecom entity in India, Bharat Sanchar Nigam Limited (BSNL) pioneered 02 CNPN projects. In mining sector, a private 5G Standalone (SA) network is installed, spanning 09 sq.km, at the Amlohri Open Cast Coal Mines in Madhya Pradesh [10].

Key highlights in the project are: Real-time video surveillance for operational monitoring, IoT-based environmental tracking sensors (air quality, temperature), Drone-based remote monitoring, Integration of digital twin technology for load-haul dump operations and Collision avoidance systems powered by cellular vehicle-to-everything (C-V2X) technology. Fig.3 shows the radio coverage in the NPN scenario.

The second project is partnering with Numaligarh Refinery Limited (NRL) in Assam, to pioneer 5G-enabled digital transformation in India's refinery sector. Key features of the project - Indigenous 5G Infrastructure with secure network architecture, URLLC to supports real-time process control and monitoring, Integration (AR/VR, IoT, Digital Twins) for immersive training and predictive maintenance and Cyber-Resilient Architecture for secure mission-critical refinery systems.

Stake Holders in a CNPN project [12] include:

1. Telecom Service Provider (TSP) – provide 5G CNPNs based on the policy frameworks and regulatory eco system.

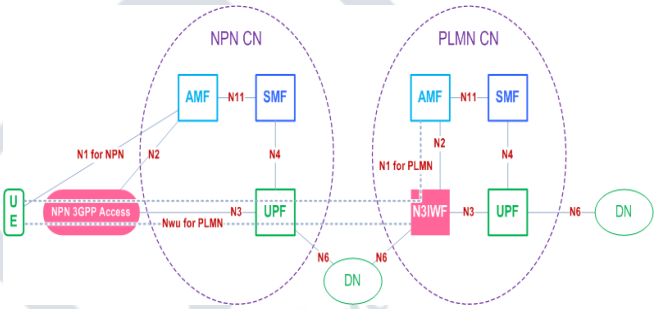


Figure 2. Access to PLMN services via Stand-alone Non-Public Network

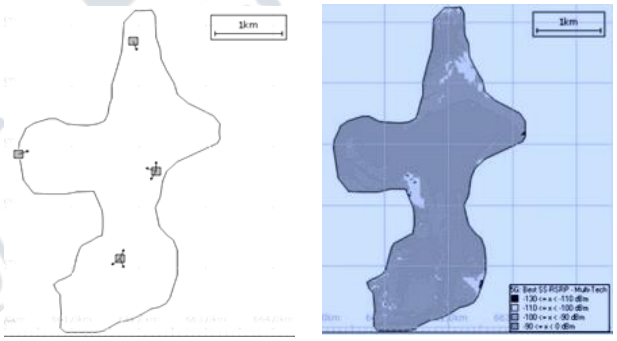


Figure 3. NR coverage in a Stand-alone Non-Public Network

2. CNPN Provider (CNPNP) – TSP will empanel partners for CNPNP projects based on the specific requirements of the client and the best price offer available.
3. Original Equipment Manufacturer (OEM) - CNPN Provider engages with OEMs for 5G equipment supply for Private Network.
4. Use Case Developers - Normally CNPN Provider does the use case development. In some cases, it is done by the end with other third party.
5. Device Manufacturers - includes handset, IoT device and other hardware manufacturers.

Latency in Public vs. Private 5G NR Networks

The latency parameter is highly significant in a CNPN implementation as it guarantees near real-time communication in the range of 1-10 milliseconds [13]. This

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enables mission-critical applications such as closed-loop robotic control and autonomous guided vehicle (AGV) collision avoidance systems. Low latency also ensures both the precision required for industrial automation and the safety response necessary for human-machine collaboration.

Latency behavior in public and private 5G NR networks differs significantly due to architectural and deployment factors. Public networks typically involve multi-hop transport, shared spectrum and centralized cores, resulting in higher and more variable end-to-end latency. In contrast, Private 5G systems deploy localized cores, dedicated spectrum and edge-based scheduling, allowing for deterministic and ultra-low latency suitable for industrial automation and mission-critical control [5] [8].

This research aims to:

(a) Develop an analytical latency model for the radio interface in private 5G NR networks, that will capture key latency components: PUCCH access delay (uplink control), PDCCH queuing delay (downlink control scheduling), PUSCH/PDCH transmission delay (data plane) and RLC/MAC retransmission delays [11].

(b) Compare performance under varying traffic loads.

Research Gaps in Latency Characterization

Despite significant progress in 5G latency modelling, several research gaps remain [16]. Current analytical and simulation frameworks often simplify cross-layer interactions, dynamic scheduling, HARQ retransmissions and queuing variability under realistic traffic loads. Latency decomposition across the RAN, transport and 5G Core is still limited, especially for private and hybrid CNPN deployments. Most models focus on average or percentile latency, lacking fine-grained temporal and spatial variability analysis critical for URLLC. Finally, AI-driven latency prediction and adaptation mechanisms are still in early stages, with limited validation against real-world 5G testbeds or industrial scenarios.

III. METHODOLOGY

The E2E latency model includes three main components (i) Radio Access Network (RAN) latency (scheduling, mini-slots, and physical layer processing in the gNB and UE), (ii) Transport Network (TN) latency (fiber/switching delays) and (iii) Core Network (CN) processing latency. The proposed framework decomposes the RAN latency into measurable segments to pinpoint bottlenecks and optimize network configuration. Schematic is shown in Fig.4.

The core logic used is: Radio Latency = Packet generation delay + Queueing delay + Scheduling delay + Transmission delay + Processing delay + Retransmission delay (if any).

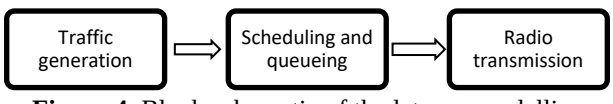


Figure 4. Block schematic of the latency modelling framework

Private network traffic is modelled as a mixture of deterministic (periodic) and stochastic (aperiodic) arrivals representing URLLC control and best-effort services [15]. For stochastic traffic, inter-arrival times are exponential distributions, while periodic traffic follows deterministic generation intervals. This approach reflects the heterogeneous traffic behaviour commonly observed in CNPN [17]. Traffic generation parameters are shown in Fig.5 and Fig.6.

Scheduling is performed at the MAC layer, where packets are buffered and served according to available radio resources. Here the assignments (PRBs, Slots, Users) are done and the Scheduling instants and Queue evolution happen. The radio block deals with the PHY latency. It computes PHY Transmission (Tx) time, HARQ (Hybrid Automatic Repeat request) and MCS (Modulation and Coding Schemes) [2].

Pseudo-Code of Latency Analysis:

Input:
Traffic model M ∈ {periodic, aperiodic, mixed},
Arrival timestamps T_a,
Service rate μ,
PRB allocation policy P,
MCS scheme S,
HARQ config H
Output:
Packet-level latency L_{RAN}
BEGIN
i. Traffic Generation:
Generate packets according to M
Record T_a
ii. MAC Queueing:
Buffer packets per user
Update queue length Q(t) ← f (λ, μ)
λ = arrival rate
μ = service rate
iii. DL Scheduling:
FOR each slot k DO
Evaluate active queues
Allocate PRBs using policy P
Compute scheduling time $T_{sched}(k)$
END FOR
iv. PHY Transmission:
Using PRBs and scheme S:
Compute transmission time T_{tx}
Evaluate HARQ retransmissions under H
v. Latency Assembly:
$L_{RAN} \leftarrow T_a + T_{sched} + T_{tx}$ + retransmission delays
RETURN L_{RAN}
END

This computes individual latency components (queueing, scheduling, transmission, processing and retransmission) for each packet and aggregate them to obtain the total latency.

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Updates resource usage statistics, including per-slot PRB allocation and cumulative resource block utilization.

IV. SYSTEM MODEL AND LATENCY COMPONENTS

The simulation aligns with the 3GPP framework by modelling the key radio latency components defined at the PHY/MAC layers.

(a). Traffic Arrival Modeling

Let $T_a^{(i)}$ denote the arrival time of the i[th] packet at the MAC layer.

For periodic traffic: $T_a^{(i)} = i \cdot T_p$

where T_p = packet generation period

For aperiodic traffic, inter-arrival times follow an exponential distribution:

$\Delta T_a \sim \text{Exp}(\lambda)$ and $T_a^{(i)} = \sum_{k=1}^{i} \Delta T_a^{(k)}$

where:

λ= packet arrival rate (packets/ms)

Mixed Traffic (CNPN Model) arrival stream is defined as:

$T_a = T_a^{periodic} \cup T_a^{aperiodic}$

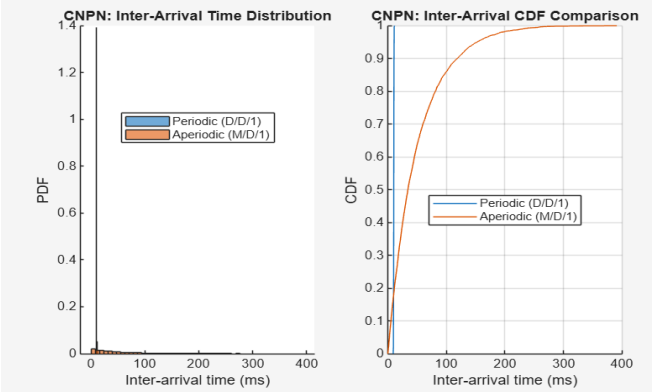


Figure 5. Periodic and Aperiodic Traffic modelling

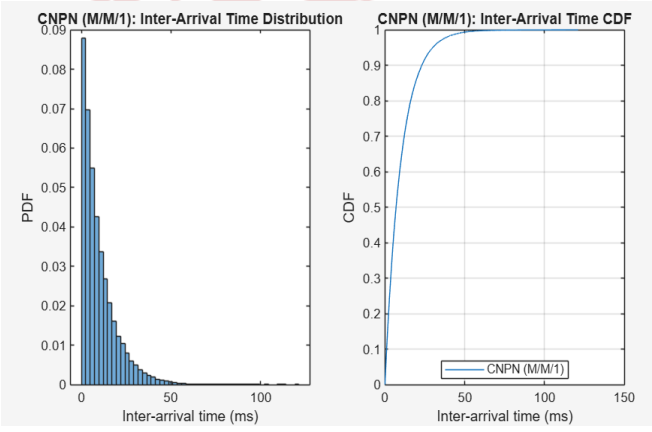


Figure 6. Random (Poisson) Traffic modelling

(b). Queueing and Scheduling (DL) Model

Packets arriving at time T_a are buffered at the MAC layer. If T_{slot} = slot duration and T_{sched} = time instant when the packet is scheduled;

Queueing Delay $D_{queue} = T_{sched} - T_a$

If the packet is aligned to the next available slot;

Scheduling Delay $D_{sched} = T_{slot}^{start} - T_{sched}$

The rule-based scheduler allocates PRBs based on - available bandwidth, active users and Queue occupancy.

(c). Transmission Latency (PHY Layer)

Let: L = packet size (bits)

R_{eff} = effective data rate (bps)

Transmission Time $D_{tx} = \frac{L}{R_{eff}}$

where $R_{eff} = N_{PRB} \cdot \eta_{MCS} \cdot f_{SCS}$

N_{PRB} : allocated PRBs

η_{MCS} : spectral efficiency of selected MCS

f_{SCS} : numerology-dependent scaling

(d). HARQ Retransmission Delay

Retransmissions are modeled using expected HARQ attempts: $D_{retx} = N_{retx} \cdot T_{retx}$

where N_{retx} : number of retransmissions

T_{retx} : HARQ round-trip delay

(e). Processing Delay

Processing delays at transmitter and receiver are modeled as constants: $D_{proc} = T_{procTx} + T_{procRx}$

(f). Final Latency Equation

$D_{final} = (T_{sched} - T_a) + D_{sched} + D_{tx} + D_{proc} + D_{retx}$

This explicit decomposition allows component-wise latency attribution.

Table 1. Simulation Observations

Parameters	Experiments	
	Variations	***Observations***
Subcarrier Spacing (SCS)	15 → 30 → 60 → 120 kHz	Higher SCS reduces slot duration, enabling faster scheduling and transmission, improving spectrum usage efficiency.
Number of UEs	10 → 600	More UEs increase queue contention and scheduling delay, leading to higher resource usage per slot.
System Bandwidth	5 → 400 MHz	More available RBs reduce contention and allow faster packet service.
MCS Index	1, 2 → 3	Higher spectral efficiency reduces required RBs per packet.
Traffic Type	Periodic → Mixed	Bursty aperiodic arrivals introduce queue fluctuations and increase latency variability.

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Parameters	Experiments	
	Variations	*Observations*
Traffic Load	Arrival rate	Increased arrivals cause queue buildup; RB utilization rises until PRBs become fully occupied.
Slot Duration	0.125 → 1	Longer slots delay scheduling opportunities, reducing responsiveness.
Retransmissions	BLER 0.01 → 0.00001	Retransmissions consume additional PRBs and increase delay variability.

V. PERFORMANCE EVALUATION AND RESULTS

CNPN deployments are characterized by: Controlled network topology, Predictable traffic patterns, Limited number of users and Dedicated spectrum resources. These characteristics are reflected in the traffic modeling and scheduling assumptions, allowing realistic evaluation of latency performance in private 5G networks.

Simulations are conducted for a private 5G NR downlink scenario with configurable:

- Traffic load and type
- Number of Users
- Bandwidth and SCS
- Scheduling policy

Latency is evaluated over multiple packet transmissions, and performance metrics are averaged across simulation runs.

The plots in Fig.7, Fig.8, Fig.9 and Fig.10 present the mean latency under different traffic conditions. Analysis shows that: At low traffic load, latency is dominated by transmission and processing delays. As traffic increases, queueing delay becomes the dominant contributor.

Role of Scheduling

The rule-based scheduler ensures fairness and predictability but does not adapt dynamically to traffic fluctuations. While this improves transparency, it limits latency optimization under bursty traffic conditions.

HARQ Effects

Retransmissions introduce additional latency variance, especially at lower MCS levels. This highlights the trade-off between reliability and latency in private 5G networks.

RB Utilisation

Higher RB utilization indicates more efficient spectrum usage, while lower utilization reflects underloaded network conditions or conservative scheduling. The metric is analysed alongside latency to study the trade-off between spectrum efficiency and delay performance in CNPN scenarios.

From the results, the inferences drawn are: latency is primarily influenced by queueing delay under high traffic and multi-user scenarios. RB utilization increases with traffic intensity and user density, reaching saturation under heavy load. Higher numerology (larger SCS) improves latency performance at the cost of increased scheduling overhead.

VI. DISCUSSION

The observed increase in latency with traffic load is primarily driven by queue build-up at the MAC layer. Since CNPN environments often support deterministic traffic, careful traffic engineering is necessary to avoid excessive buffering delays.

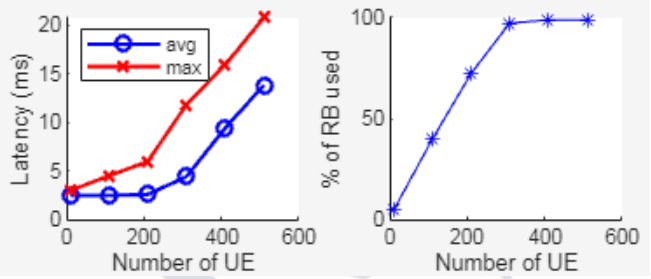


Figure 7. Ouput for simulation run: Tp=20 ms, SCS=15 KHz

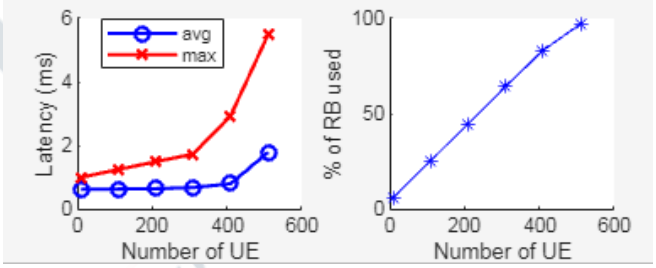


Figure 8. Ouput for simulation run: Tp=20 ms, SCS= 60 KHz

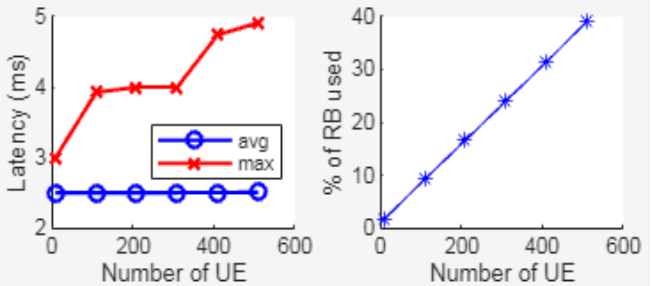


Figure 9. Ouput for simulation run: Tp=100 ms, SCS= 15 KHz

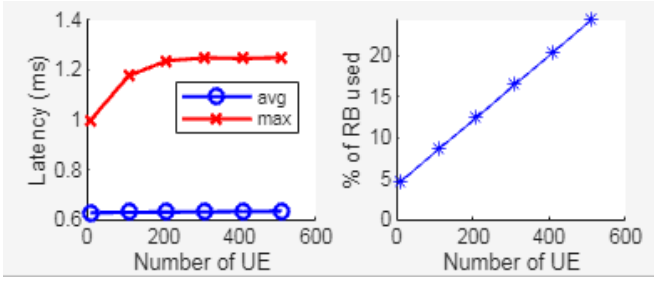


Figure 10. Ouput for simulation run: Tp=100 ms, SCS= 60 KHz

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Relevance to CNPN Deployments

The results demonstrate that component-based modeling provides actionable insights into latency bottlenecks, making the proposed framework suitable for:

- Industrial automation
- Campus networks
- Mission-critical CNPN services

Limitations and Extensions

While this work focuses on analytical and deterministic scheduling, the framework can be extended to include adaptive or learning-based schedulers, without altering the core latency model.

Use cases – Present and Future

The deployments currently support VoNR (Voice over New Radio) – Voice Calls within the Mine, ViNR (Video over New Radio) – Video Call within the Mine, Traffic Management System, Camera based Shovel Operation, Surveillance & Security system.

The future plans include Digital Twin of Coal Mine, Drone based daily inspection and survey, Remote-controlled Machinery, Collision avoidance System, Autonomous Trucks and Drilling Equipment, Wearables to workers.

Sustainable Development Goals

SDGs involved in the project are: 8-Decent work and economic growth, 9-Industry, innovation and infrastructure, 12-Responsible consumption and production, 17-Partnerships for the goals.

VII. CONCLUSION & FUTURE WORK

This work proposed a modular, component-based framework for evaluating radio latency in 5G NR Captive Non-Public Networks. By explicitly decomposing latency into traffic generation, MAC layer queueing and scheduling, physical layer transmission, processing, and retransmission components; the proposed methodology provides clear visibility into the sources of latency within a private 5G downlink system.

Through analytical modelling and simulation, it is seen that queueing delay at the MAC layer dominates overall latency as traffic load increases, particularly in mixed traffic scenarios typical of CNPN deployments. Additionally, HARQ retransmissions are observed to introduce significant variability and tail latency, which highlights the trade-off between reliability and latency in private networks. The use of deterministic, rule-based scheduling ensured reproducibility and enabled transparent analysis of scheduler-induced delays.

The proposed framework avoids reliance on proprietary or untraceable implementations and is fully aligned with 5G NR principles. It is suitable for academic research and practical performance evaluation.

Future works should focus on developing cross-domain latency models which integrate radio, transport, and core delays under realistic 5G traffic dynamics. The inclusion of AI/ML-based schedulers can enable predictive and adaptive latency control and improve QoS. Hybrid analytical frameworks can be extended to capture fine details of IoT and edge/cloud processing delays.

Private 5G NR networks provide detailed radio and network measurements such as end-to-end latency, jitter, block error rate (BLER), PRB utilization, QoS flow performance, and energy efficiency. These metrics can be used for higher-level optimization, including AI-based scheduling and coordinated network management across multiple domains. Research should look beyond to 6G and other emerging technologies. Experimental validation using real-world testbeds or digital twins will be crucial to bridge the gap between theoretical models and deployable solutions.

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REFERENCES

[1] 3GPP, “System Architecture for the 5G System (5GS); Stage 2 (Release 16),” 3GPP TS 23.501, v16.9.0, Dec. 2020.

[2] 3GPP TS 38.211, “NR; Physical channels and modulation,” 3rd Generation Partnership Project, Sophia Antipolis, France, Release 17, 2023.

[3] 3GPP, “Study on Communication for Automation in Vertical Domains (Release 16),” 3GPP TR 22.804, v16.2.0, Mar. 2018.

[4] 3GPP, “Study on Scenarios and Requirements for Next Generation Access Technologies (Release 14),” 3GPP TR 38.913, v14.3.0, June 2017

[5] ITU Radiocommunication Study Groups, “Final Evaluation Report from the 5G Infrastructure Association on IMT-2020 Proposals IMT-2020/14, 15, 16 parts of 17,” Document 5D/50-E, Feb. 2020.

[6] ITU-T, “Network Performance Objectives for IP-based Services,” ITU-T Recommendation Y.1541, Dec. 2019.

[7] IEEE, “IEEE Standard for Time-Sensitive Networking for Fronthaul,” IEEE Std 802.1CM-2018, June 2018.

[8] IEEE, “IEEE Standard for Local and Metropolitan Area Networks—Bridges and Bridged Networks – Amendment 25: Enhancements for Scheduled Traffic,” IEEE Std 802.1Qbv-2016, Mar. 2016.

[9] S. Ojha, “5G Captive Non-Public Networks: Building a flexible and inclusive policy regime in India,” ICRIER, Policy Brief, Nov. 2022. Available: https://icrier.org/invict/Policy-Brief_5G-PCNs-in-India.pdf. [Accessed: Oct. 22, 2025].

[10] BSNL Enterprise, “Private 5G - Captive Non-Public Network (CNPN),” BSNL. Available: https://bsnl.co.in/enterprise/private5g. [Accessed: Dec. 22, 2025].

[11] M. C. Lucas-Estañ *et al.*, "An Analytical Latency Model and Evaluation of the Capacity of 5G NR to Support V2X Services Using V2N2V Communications," in IEEE Transactions on Vehicular Technology, vol. 72, no. 2, pp. 2293-2306, Feb. 2023, doi: 10.1109/TVT.2022.3208306.

[12] Günter Knieps, Johannes M. Bauer, “Internet of things and the economics of 5G-based local industrial networks”, Telecommunications Policy, Volume 46, Issue 4, 2022, 102261, ISSN 0308-5961, https://doi.org/10.1016/j.telpol.2021.102261.

[13] G. Pocovi, T. Kolding and K. I. Pedersen, "On the Cost of Achieving Downlink Ultra-Reliable Low-Latency Communications in 5G Networks," in IEEE Access, vol. 10, pp. 29506-29513, 2022, doi: 10.1109/ACCESS.2022.3158361.

[14] Aijaz, "Private 5G: The Future of Industrial Wireless," in IEEE Industrial Electronics Magazine, vol. 14, no. 4, pp. 136-145, Dec. 2020, doi: 10.1109/MIE.2020.3004975.

[15] P. Popovski *et al.*, "Wireless Access for Ultra-Reliable Low-Latency Communication: Principles and Building Blocks," in IEEE Network, vol. 32, no. 2, pp. 16-23, March-April 2018, doi: 10.1109/MNET.2018.1700258.

[16] S. K. Sharma, I. Woungang, A. Anpalagan and S. Chatzinotas, "Toward Tactile Internet in Beyond 5G Era: Recent Advances, Current Issues, and Future Directions," in IEEE Access, vol. 8, pp. 56948-56991, 2020, doi: 10.1109/ACCESS.2020.2980369.

[17] M. Wen *et al.*, "Private 5G Networks: Concepts, Architectures, and Research Landscape," in IEEE Journal of Selected Topics in Signal Processing, vol. 16, no. 1, pp. 7-25, Jan. 2022, doi: 10.1109/JSTSP.2021.3137669