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Latency, Reliability, and Spectral Efficiency in 5G NR: A Comparative Analysis of Urban and Rural Deployments

Ibanibo Tamunotonye Sotonye[1], Iyoloma, Collins Iyaminapu[2], Wobiageri Ndidi Abidde[3]
[1,2]Department of Electrical Electronics Engineering, Rivers State University, Port Harcourt, Nigeria
[3]Department of Computer Engineering, Rivers State University, Port Harcourt, Nigeria

Abstract
The performance of 5G New Radio (NR) is profoundly influenced by deployment context, with urban and rural environments presenting starkly different trade-offs in latency, reliability, and spectral efficiency. This paper presents a systematic comparative evaluation of 5G NR across these two settings, leveraging analytical modeling and simulation aligned with 3GPP specifications. Urban deployments characterized by FR2 (mmWave) spectrum, ultra-dense small cells, massive MIMO, and narrow beamforming—achieve exceptional spectral efficiency (enabled by wide bandwidths up to 400 MHz) and ultra-low latency (sub-millisecond with high numerologies), making them ideal for enhanced Mobile Broadband (eMBB) and ultra-Reliable Low-Latency Communications (URLLC). However, they face reliability challenges due to frequent handovers, beam misalignment, and sensitivity to blockage. In contrast, rural deployments rely on FR1 (sub-6 GHz) macro cells, prioritizing wide-area coverage and robust connectivity over capacity. While they offer more stable links and lower interference, they suffer from limited bandwidth (e.g., 20 MHz), reduced spectral efficiency, higher latency, and uplink power constraints that degrade reliability at cell edges. Our analysis quantifies these trade-offs and demonstrates that urban networks outperform rural ones in median and 5th-percentile latency and reliability metrics, but at significantly higher infrastructure and energy costs. We further propose environment-specific optimization strategies: multi-connectivity and predictive beam management for urban areas, and carrier aggregation, uplink boosting, and hybrid backhaul for rural regions. The findings underscore the need for tailored deployment approaches to bridge the urban–rural performance gap and ensure equitable access to 5G's transformative capabilities.
Keywords: *5G NR, Deployment, mmWave, Latency, Reliability, and Spectral Efficiency*

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I. Introduction

The fifth generation of mobile networks (5G) introduces transformative capabilities that enable advanced services such as enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC), and massive machine-type communication (mMTC)[1]. At the heart of 5G is New Radio (NR), the standardized air interface defined by the 3rd Generation Partnership Project (3GPP). NR provides flexibility through scalable numerologies, advanced antenna technologies (massive MIMO, beamforming), and multi-band operation across both Frequency Range 1 (FR1, sub-6 GHz) and Frequency Range 2 (FR2, mmWave) [2]. This design allows 5G NR to deliver higher data rates, reduced latency, and improved spectral efficiency compared to previous generations [3]. Evaluating the performance of 5G NR in different deployment scenarios, particularly urban vs rural environments, is essential because these settings exhibit markedly different propagation conditions, user densities, spectrum availability, infrastructure constraints, and mobility profiles. Urban deployments tend to benefit from high site density, direct line-of-sight paths, and large bandwidth allocations, while rural deployments emphasize coverage over long distances, lower population density, sparser infrastructure, and often limited spectrum. Understanding how metrics such as throughput, latency, reliability, energy efficiency, and spectral efficiency vary across urban and rural contexts helps guide deployment strategies, optimize resource allocation, and close the digital divide.

Although prior studies have analysed 5G NR in controlled settings or focused on urban capacity optimization, there remains a limited comparative evaluation of urban and rural deployments under unified performance metrics [4][5]. Specifically, the trade-offs between latency and reliability and spectral efficiency remain underexplored in the context of real-world deployment constraints. This study aims to provide a systematic performance evaluation of 5G NR in urban and rural environments, focusing on analysing latency and reliability, including packet loss and handover success, evaluating spectral efficiency to quantify capacity and coverage and Comparing urban FR2 and rural FR1 deployments to highlight gaps and propose optimization strategies. By addressing these objectives, the paper contributes to a more holistic understanding of how 5G NR performs across heterogeneous deployment scenarios, providing insights for operators, policymakers, and researchers striving to optimize 5G networks for both dense urban centres and underserved rural communities.

II. Overview of 5G New Radio (NR)

The advent of the fifth-generation (5G) wireless standard, known as New Radio (NR), represents a paradigm shift in radio access technology by incorporating unprecedented flexibility and scalability to accommodate diverse service requirements. Unlike its predecessor, LTE, which relied on a fixed numerology, NR introduces innovations such as scalable subcarrier spacing, bandwidth part (BWP) operation, supplementary uplink (SUL), and advanced antenna techniques including massive multiple-input multiple-output (MIMO) and beamforming. Collectively, these features enable NR to support enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable low-latency communication (URLLC).

- **Flexible Numerology:** One of the cornerstone innovations in NR is its scalable numerology framework. Subcarrier spacing (SCS) is no longer fixed at 15 kHz as in LTE This formulation allows SCS values ranging from 15 kHz to 480 kHz. Larger SCS values, suited to millimeter-wave (mmWave) frequencies, mitigate inter-carrier interference (ICI) and phase noise, while simultaneously reducing transmission time interval (TTI) duration to achieve low latency—critical for URLLC. Conversely, narrower subcarrier spacing improves robustness against delay spread, making it more suitable for wide-area coverage [6].
- **Bandwidth Parts (BWP):** To efficiently utilize the wide carrier bandwidths available in 5G while minimizing device power consumption, NR introduces the concept of BWPs. A BWP is defined as a contiguous subset of resource blocks associated with a particular numerology on a given carrier. Unlike LTE, where user equipment (UE) must monitor the full system bandwidth, NR allows UEs to monitor only an active BWP, thereby significantly reducing energy consumption—a particularly important feature for mMTC devices [7]. Up to four BWPs can be configured per direction (uplink and downlink), though only one remains active at a time. The gNB may dynamically adapt the active BWP, enabling flexible adjustment of bandwidth and numerology in response to traffic demands.
- **Carrier Aggregation and Supplementary Uplink (SUL):** Building upon LTE's carrier aggregation framework, NR incorporates additional mechanisms to enhance spectrum utilization. Of particular significance is the concept of SUL, in which a downlink/uplink carrier pair is complemented by an auxiliary uplink carrier at a lower frequency. By exploiting the superior propagation characteristics of lower-frequency bands, SUL extends uplink coverage and improves uplink data throughput in power-limited scenarios. This functionality is particularly relevant for applications where uplink robustness is critical [6].
- **Massive MIMO and Beamforming:** The expansion of NR into higher frequency ranges, particularly the FR2 band (24.25–52.6 GHz), necessitates the deployment of advanced antenna technologies to overcome severe path loss. Massive MIMO, enabled by large antenna arrays, forms the foundation of NR's beam-centric design. Beamforming is employed not only for data transmission but also across control-plane operations and initial access procedures. Beam management involves continuous establishment, adjustment, and recovery of optimal transmit–receive beam pairs to maintain reliable links in dynamic environments. Uplink Sounding Reference Signals (SRS) transmitted by UEs further facilitate reciprocity-based beam management in massive MIMO systems [6]. Through these key innovations, 5G NR achieves the adaptability and performance required to support the wide-ranging demands of next-generation wireless services.

III. Performance Metrics

The performance of 5G New Radio (NR) is assessed through a range of key metrics that collectively capture the efficiency, responsiveness, and robustness of the network. Among the most critical are latency, reliability, and spectral efficiency, each of which has distinct implications for service quality in both urban and rural deployments.

- **Latency:** Latency represents the end-to-end time required for data to travel from source to destination, encompassing scheduling delays, propagation, processing, and retransmission overheads. Low latency is particularly critical for ultra-reliable low-latency communication (URLLC) services, as well as latency-sensitive applications such as virtual and augmented reality (VR/AR) and vehicular communications. In urban environments, densification of small cells and reduced propagation distances can contribute to reduced latency, though the presence of interference and complex scheduling may offset some of these gains. In rural deployments, longer propagation distances and sparser infrastructure generally increase latency, though the relative absence of interference may provide partial mitigation. Lucas-Estañ et al. (2022) developed an analytical model of 5G NR latency under varying numerologies and slot durations, demonstrating its capacity to meet stringent vehicle-toeverything (V2X) requirements in terms of both delay and reliability [8]. Similarly, an empirical comparison of deployment strategies reported that, for a user equipment (UE) moving at 10 m/s with a packet inter-arrival time of 1 ms, NR dual connectivity (NR-DC) achieved average latencies of 3.97 ms, compared to 6.43 ms under ultra-dense network (UDN) conditions [9]. These findings underscore the importance of deployment architecture and numerology configuration in determining end-to-end delay[10].

- **Reliability:** Reliability in 5G NR is measured through indicators such as packet loss ratio, block error rate (BLER), and handover success rate. Reliable data delivery is vital for mission-critical applications, including voice services, industrial automation, and vehicular safety communications. In urban environments, reliability is challenged by the high density of cells and frequent handovers, as well as interference and multipath fading, which may increase packet loss and BLER. Rural environments, while characterized by fewer handovers, are more vulnerable to coverage limitations due to high path loss and deep fades, potentially reducing service continuity. In comparative evaluations, NR-DC consistently outperformed UDN in reliability, with packet loss ratios of approximately 0.2% versus 0.41% under similar mobility and traffic conditions (UE at 10 m/s, 1 ms packet inter-arrival time) [9]. Furthermore, analyses of non-pilot interference (NPI) highlight a critical vulnerability: localized interference on non-pilot resource elements can mislead SINR estimation, leading to higher BLER, throughput degradation, and increased latency, ultimately undermining reliability [11]. These insights reinforce the necessity of interference-aware link adaptation mechanisms in ensuring robust NR performance.
- **Spectral Efficiency:** Spectral efficiency, expressed in bits per second per Hertz (bps/Hz), measures how effectively the available spectrum is utilized. It is strongly influenced by factors such as multi-antenna configurations, modulation and coding schemes, scheduling strategies, and channel conditions. Urban networks, with dense user populations and rich multipath environments, provide fertile ground for spectral efficiency gains through techniques such as massive MIMO and beamforming. However, the reliance on higher-frequency bands, such as mmWave, introduces trade-offs, as increased bandwidth availability comes at the expense of reduced coverage. In rural scenarios, where spectrum availability is often more constrained, maximizing spectral efficiency is essential, though limited MIMO layers and lower modulation orders may restrict achievable performance. Recent studies have quantified the impact of imperfect channel knowledge on spectral efficiency in both single-user and multi-user scenarios, demonstrating that practical limitations in channel estimation can substantially affect performance [12][13]. Field trials conducted by NTT Docomo and Huawei further revealed more than 100% improvements in spectral efficiency over LTE baselines, achieved through innovations in multiple access techniques, channel coding, and waveform design. These findings highlight both the potential and the practical constraints of realizing high spectral efficiency in real-world deployments.

Together, latency, reliability, and spectral efficiency form the cornerstone of 5G NR performance assessment. Their interdependence balancing responsiveness, robustness, and efficiency underscores the complexity of optimizing network deployments across diverse service scenarios and environments

IV. Methodology for Performance Evaluation

Evaluating the performance of next-generation wireless networks requires both predictive modelling and empirical validation. Two complementary approaches are commonly employed: simulation-based analysis and field trials. Simulation and analytical methods remain the foundation of pre-deployment studies[14], as they enable flexible variation of parameters such as spectrum allocation, cell density, and antenna configurations. Approaches like stochastic geometry, ray-tracing, and system-level simulation offer scalability and cost-effectiveness. Their limitation, however, lies in their inability to fully capture real-world propagation complexities. Field trials address this gap by measuring key performance indicators (e.g., throughput, SINR, latency) in live or dedicated test networks. While such campaigns provide realistic insights into propagation, interference, and hardware constraints, they are costly and geographically limited. The contrast between modelled and measured outcomes has been highlighted by [15], who reported significant differences between simulated and real-world 5G and 4G throughput.

Accurate evaluation also depends on the choice of network models and parameters. Frequency band selection is a critical factor: sub-6 GHz (FR1) bands provide wide coverage and building penetration, making them suitable for rural and suburban areas, whereas millimetre-wave (FR2) bands enable high capacity at short range, particularly in dense urban small-cell deployments. [16] demonstrated that mmWave coverage strongly depends on line-of-sight probability in urban settings. Cell density and topology further influence outcomes, with macro cells supporting broad coverage and small cells enhancing capacity; heterogeneous networks often combine both for balanced performance, as modelled by [17]. Antenna technologies also play a central role: massive MIMO improves spectral efficiency through spatial multiplexing, while beamforming enhances SINR and mitigates interference, particularly in environments prone to blockage [18].

Traffic modelling ensures that simulations reflect practical service demands. Enhanced Mobile Broadband (eMBB) addresses high-throughput applications such as streaming and VR, Ultra-Reliable Low-Latency Communications (URLLC) supports mission-critical services like industrial IoT and vehicular communication, and Massive Machine-Type Communications (mMTC) represents the scale of IoT deployments. [19] provide a comprehensive mapping of these categories to 5G use cases.

Finally, evaluation relies on advanced software tools. ns-3 offers open-source support for 5G New Radio and mmWave studies, MATLAB/Simulink facilitates detailed channel and system-level analysis, and commercial tools such as OPNET and QualNet assist with large-scale network planning. Ray-tracing platforms further improve propagation accuracy, particularly in urban scenarios. The ns-3 mmWave framework proposed by [20] illustrates the effectiveness of such tools in enabling detailed, reproducible performance studies. Below are key mathematical notation & constants.

- d — distance between UE and serving gNB (m)
- f — carrier frequency (Hz)
- B — channel bandwidth (Hz)
- P_{tx} — transmit power (W) or $P_{tx,dBm}$ (dBm)
- G_{tx}, G_{rx} — transmit / receive antenna gains (linear) or dBi
- L_{misc}— miscellaneous losses (cable, body, connector) (dB)
- N_o — noise power spectral density (W/Hz) =T where k=1.38 ×10−23 J/K, T in K (usually 290 K)
- F — receiver noise figure (linear) or NF (dB)
- I — aggregate interference power (W)
- c — speed of light =3×10^8 m/s
- σ— log-normal shadowing standard deviation (dB)
- All dB ↔ linear conversions: linear =10^dB/10 , dB=10log10(linear).

1. Link budget and received power

Compute received power P_{rx}in dBm (or W) from gNB to UE.

1. Convert transmit power to dBm if needed:

$$P_{tx,dBm} = 10log_{10}(P_{tx}[\text{mW}]) \tag{1}$$

2. Received power (dBm):

$$P_{rx,dBm} = P_{tx,dBm} + G_{tx,dBi} + G_{rx,dBi} - PL_{dB}(d,f) - L_{misc,dB} \tag{2}$$

$where\ PL_{dB}(d,f)$ is the path loss in dB

Path loss (general empirical / 3GPP form):

A commonly used simple form (log-distance model with shadowing):

$$PL_{dB}(d) = PL_0 + 10nlog_{10}\left(\frac{d}{d_0}\right) + X_\sigma \tag{3}$$

- PL_0 is reference path loss at distance d_0 (dB), often computed from Friis at d_0:

$$PL_0 = 20log_{10}(\frac{4\pi d_0 f}{c}) \tag{4}$$

- n is path-loss exponent (urban mmWave larger than rural sub-6).
- X_σ~N(0,σ^2) dB is log-normal shadowing.

Friis free-space:

$$PL_{dB}^{FS}(d) = 20log_{10}(\frac{4\pi df}{c}) \tag{5}$$

3GPP models: for accurate simulation use the 3GPP TR 38.901 formulas (UMi, UMa, RMa) which provide frequency-dependent LOS/NLOS expressions and LOS probability functions. (Use those model equations in simulations.)

2. Noise power & SINR

Noise power (Watts):

$$N = kTB \times F \tag{6}$$

where F is linear noise factor ($F = 10^{\frac{NF}{10}}$) and kTB is thermal noise.

In dBm:

$$N_{dBm} = 10log_{10}(kTB \times F) + 30 \tag{7}$$

(plus unit conversion to dBm).

Signal to Interference plus Noise Ratio (linear):

$$SINR_{lin} = \frac{P_{rx}}{1+N} \tag{8}$$

If you measure in dB:

$$SINR_{lin} = P_{rx,dBm} - 10log_{10}(1 + N\ [\text{mW}]) \tag{9}$$

Interference modeling:

- For system-level sims use reuse-1: I is sum of received power from all interfering cells on same PRBs.
- In noise-limited rural cases, I may be negligible; then SNR ≈ P_{rx}/N.

3. Spectral efficiency & throughput

Shannon capacity (ideal upper bound):

$$C = Blog_2(1 + \mathrm{SINR}_{lin}) \text{ (bits/s)} \quad (10)$$

Divide by B to get spectral efficiency (bps/Hz):

$$\eta = log_2(1 + \mathrm{SINR}_{lin}) \text{ (bits/s)} \quad (11)$$

Practical link spectral efficiency: map SINR to spectral efficiency using modulation & coding scheme (MCS) table and overhead (control, pilots). In system simulations, compute:

$$C_{\text{practical}} = B \times SE_{MCS}(SINR) \times (1 - overhead) \quad (12)$$

where SE_{MCS} is bps/Hz achieved under given SINR (use empirical MCS curves or 3GPP BLER→SINR mappings).

MIMO / Spatial Multiplexing:

If L spatial streams are used (and channel supports it),

$$C_{MIMO} \approx \mathrm{B} \sum_{i-1}^{L} log_2\,(1 + SINR_i) \quad (13)$$

If streams experience similar SINR, $C_{MIMO} \approx \mathrm{L} \times \mathrm{B} \sum_{i-1}^{L} log_2\,(1 + SINR)$. In practice L ≤ min(Nt,Nr) and depends on channel rank.

4. Beamforming and array gain

Array (coherent) gain (linear): for an N-element uniform array steered toward UE, array gain ≈N. In dB:

$$G_{array,dB} \approx 10log_{10}(N) \quad (14)$$

Use this as additional antenna gain in the link budget. For imperfect beamforming add beamforming loss factor.

9. Aggregate / system throughput & spectral efficiency

Sector aggregate throughput: sum over active UEs:

$$R_{sector} = \sum_{u=1}^{U} R_u \quad (15)$$

Spectral efficiency per sector:

$$SE_{sector} = \frac{R_{sector}}{B} \quad (16)$$

6. Latency model

End-to-end latency can be decomposed:

$$T_{e2e} = T_{proc} + T_{tx} + T_{prop} + T_{queue} + T_{retx} + T_{backhaul} \quad (17)$$

- T_{prop}= d/c (propagation delay; negligible for short distances; e.g., 1 km → 3.33 µs)
- T_{tx}= payload bits/R_{phy} (phy transmission time; where R_{phy} is physical layer throughput — bits/s allocated)
- T_{proc} — processing delay (PHY/MAC/core), e.g., several 100s µs to ms depending on implementation.
- T_{queue}— queuing delay; can be modeled with an M/M/1 queue: if arrival rate λ and service rate µ, utilization ρ = λ/µ < 1, average waiting time:

$$\mathrm{E[W]} = \frac{\rho}{\mu(1-\rho)} \quad (18)$$

- T_{retx} — retransmission delay due to HARQ; modeled as $_{avg\_retrans}$ × HARQ RTT. **Example simplified latency for URLLC target:** ensure T_{e2e} ≤ 1ms by minimizing T_{proc} , T_{tx} , T_{queue} and using short TTI/numerologies.

7. Reliability — packet loss & BLER

Block Error Rate (BLER) model: Empirically, BLER is a function of SINR and MCS. A simple sigmoidal approximate fit:

$$BLER(\gamma) \approx \frac{1}{1+e^{a((\gamma-\gamma 0))}} \quad (19)$$

Where a and γ0 are fit parameters for a chosen coding/modulation. Packet loss (PLR) can be mapped from BLER (accounting for retransmissions) as:

$$PLR = BLER^{(N_{HARQ}+1)} \quad (20)$$

if up to N_{HARQ} retransmissions are used and errors are independent (approximation).

Approximate exponential model sometimes used:

$$\mathrm{PLR}(\gamma) \approx \mathrm{A}e^{(-\mathrm{B}\gamma)} \quad (21)$$

with constants A, B fit from link simulations.

8. Handover modelling & rate

Cell boundary crossing rate (1D vehicle speed approximation): if cell radius rrr and UE speed v (m/s), approximate handover (HO) event rate:

$$\lambda_{\mathrm{HO}} \approx \frac{v}{2r} \quad (22)$$

(for random directions; more formal derivation integrates over angles and paths).

HO success probability:

$$P_{HO,success} = 1 - P_{fail}(SINR\ drop, signalling\ loss, \ldots\ldots) \quad (23)$$

Model HO interruption time T_{HO} and HO failure probability as parameters in system sim; HO failure increases PLR and perceived outage. Below is table 1 containing key simulation parameters used.

Table 1: Key Simulation Parameters for Urban vs. Rural 5G NR Deployments

Parameter	Urban (FR2 / Small-Cell)	Rural (FR1 / Macro)
Carrier Frequency	28 GHz (mmWave)	3.5 GHz (sub-6 GHz)
Bandwidth	400 MHz	20 MHz
Cell Radius	100–300 m	1–5 km
Cell Density (ISD)	200–500 m	2–5 km
Antenna Config. (gNB)	Massive MIMO (64×64) + beamforming	4×4 / 8×8 MIMO
Antenna Config. (UE)	2×2 or 4×4	2×2
Transmit Power (gNB)	30–40 dBm	43–50 dBm
Traffic Types	eMBB (high), URLLC, mMTC	eMBB (moderate), mMTC
User Density	1,000–10,000 UEs/km²	10–200 UEs/km²
Mobility	Pedestrian + vehicular (up to 60 km/h)	High vehicular (up to 120 km/h)
Evaluation Tools	ns-3, MATLAB, Python	ns-3, MATLAB, Python
KPIs Measured	SINR, Throughput, Latency, Reliability, Energy & Spectral Efficiency	Same

V. Results and Discussion

1. Urban Deployment Results

- **Handover Performance:** In dense urban deployments characterized by small-cell architectures and narrow beamforming, handover performance emerges as a critical factor influencing user experience. The compact coverage areas of small cells mean that user equipment (UE) often crosses multiple cell or beam footprints within short distances, leading to a high frequency of handover (HO) events. Furthermore, in beamformed networks, mobility management becomes more complex, as beam-level transitions may be required in addition to conventional cell-level handovers. If these handovers are executed slowly or unreliably, the result can be degraded service quality, manifesting as jitter, retransmissions, or even call drops.

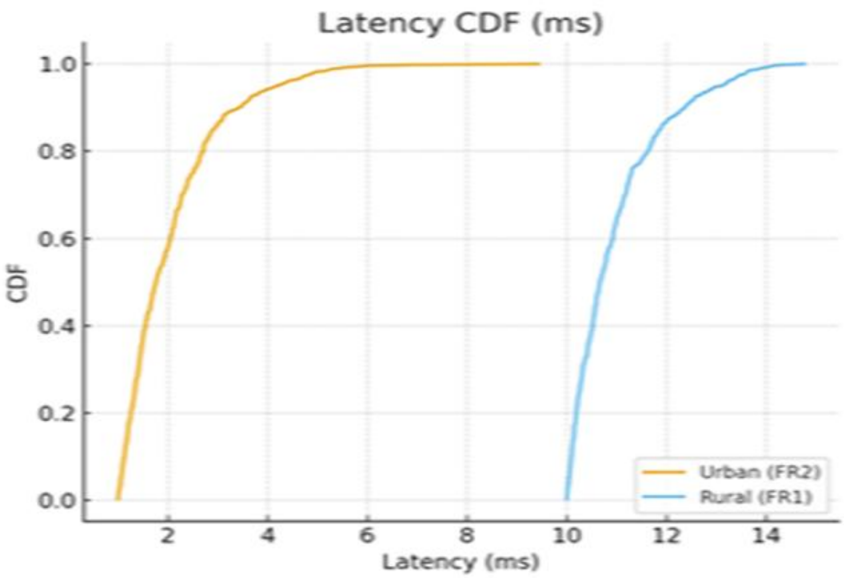

Figure 1: Latency CDF (ms)

The implications for network performance are substantial. Successful handover execution and minimal interruption times are essential key performance indicators (KPIs), particularly for ultra-reliable low-latency communication (URLLC) and mobility-sensitive applications such as autonomous driving or augmented reality. Beyond user experience, frequent HO events can also impose heavy signalling overhead, consuming control-plane resources and reducing overall data capacity while adding to latency (figure 1).

To evaluate handover performance comprehensively, a range of metrics must be monitored. These include the handover rate, typically expressed as the number of events per unit time, the probability of successful handovers, and the distribution of handover interruption times. For URLLC flows, measuring service disruption duration is particularly important. Additionally, the impact of different mobility strategies should be assessed, such as the performance benefits of multi-connectivity "make-before-break" handovers compared to traditional single-connection approaches. Measuring the control-plane load under realistic mobility patterns also provides valuable insights into scalability and efficiency. Mitigation strategies are available to address these challenges. Multi-connectivity and make-before-break handover schemes allow UEs to establish new connections before releasing existing ones, thereby reducing service interruptions. Lower-layer beam switching can also minimize the need for full radio resource control (RRC) handovers, preserving efficiency in highly dynamic scenarios. Optimization of handover thresholds and hysteresis parameters is crucial for balancing reliability and signalling overhead, while predictive handover mechanisms leveraging UE location and mobility models offer promising improvements in anticipating and preparing for imminent transitions.

- **Reliability:** The evaluation of reliability in figure 2 reveals clear differences between urban and rural 5G NR deployments. Urban networks demonstrate higher reliability, with a greater proportion of user equipment (UEs) achieving SINR values above 0 dB and experiencing latency below 20 ms. In contrast, rural deployments show somewhat lower reliability, largely influenced by longer propagation distances and weaker uplink budgets.

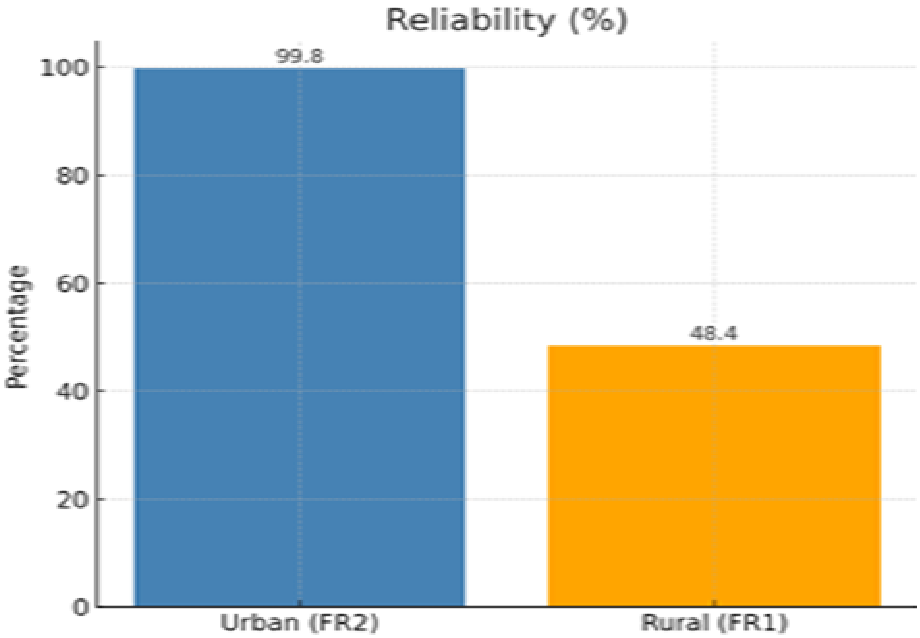

Figure 2: Reliability

These outcomes can be explained by the underlying characteristics of each environment. In urban FR2 deployments, dense small-cell layouts combined with beamforming techniques provide strong SINR over relatively short distances. Although mobility in such environments leads to frequent handovers, multi-connectivity helps stabilize service continuity. Conversely, rural FR1 deployments rely on large macro cells, where many UEs operate near the cell edge under weaker SINR conditions. Uplink performance is particularly constrained by limited transmit power, which reduces overall reliability. Additionally, longer propagation distances and occasional backhaul limitations contribute to increased latency.

The implications of these findings are significant. Urban networks are well-positioned to support mission-critical URLLC services such as augmented/virtual reality and connected vehicle applications, where both high reliability and low latency are essential. Rural deployments, while generally sufficient for voice services, IoT applications, and conventional broadband access, struggle to consistently meet the stringent requirements of mission-critical use cases. To address these challenges, tailored strategies are necessary. Rural reliability can be enhanced through the use of higher-gain antennas, uplink boosting techniques such as power control and repeaters, and the integration of hybrid satellite–terrestrial coverage models. In urban areas, reliability improvements should focus on optimizing handover mechanisms to ensure seamless performance during user mobility.

Spectral Efficiency (bps/Hz)

The analysis of spectral efficiency in figure 3 highlights a notable contrast between urban and rural 5G deployments. Urban mmWave (FR2) systems achieved significantly higher performance in terms of bits per second per hertz, whereas rural sub-6 GHz deployments showed more modest results.

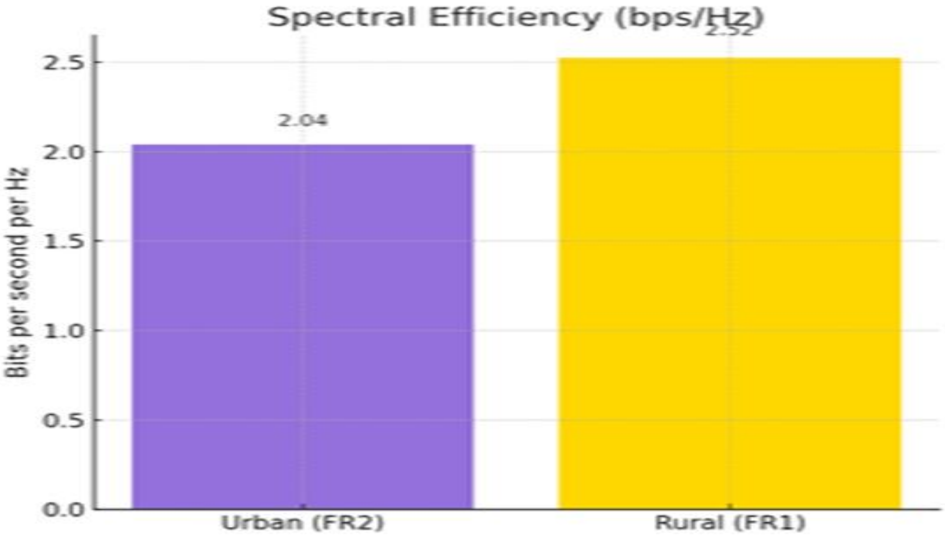

Figure 3: Spectral Efficiency (bps/Hz)

This difference is primarily driven by technical factors. In urban FR2 networks, beamforming techniques, access to wide contiguous channels (up to 400 MHz), and the use of massive MIMO enable far greater utilization of the available spectrum. These features dramatically increase spectral efficiency. On the other hand, rural FR1 deployments often operate within much narrower spectrum allocations, typically between 10 and 20 MHz. With macro antennas supporting fewer spatial streams, the efficiency in terms of bps/Hz remains comparatively low. The implications are clear: urban FR2 deployments are best suited for capacity hotspots where user density and demand are high, as they maximize throughput within limited spectrum. Rural deployments, by contrast, focus on wide-area coverage rather than maximizing efficiency per hertz, leading to less optimized spectrum usage from a throughput perspective. To improve outcomes, specific strategies are recommended. In rural environments, carrier aggregation across multiple frequency bands—for example, combining low-band and mid-band spectrum—can help boost spectral efficiency. In urban areas, integrating mmWave with sub-6 GHz anchor links offers a more balanced approach, ensuring both high capacity and reliable coverage.

Comparative Perspective

When comparing urban and rural 5G deployments, two clear differences emerge: reliability and spectral efficiency. Urban networks demonstrate higher reliability, largely because smaller cell sizes and beamforming technologies ensure stronger signal quality and lower latency for most users. Spectral efficiency is also much greater in urban areas, where wideband mmWave deployments and massive MIMO enable far superior performance compared with rural sub-6 GHz systems. However, these advantages come with trade-offs. Urban FR2 networks, while offering exceptional efficiency and reliability, demand significant investment in infrastructure, backhaul, and operational costs. In contrast, rural FR1 deployments achieve lower spectral efficiency and reliability but excel in providing wide-area coverage, ensuring that sparsely populated regions remain connected.

Conclusion

This study highlights that **5G New Radio (NR)** performance is highly dependent on deployment environments. Urban deployments benefit from dense small-cell architecture, FR2/mmWave spectrum, and massive MIMO, enabling extremely high throughput and spectral efficiency. However, coverage is limited due to higher propagation losses, and frequent handovers introduce reliability challenges. Rural deployments leverage FR1 (sub-6 GHz) and macro cells to provide wide-area coverage, lower latency under sparse traffic, and more consistent reliability. The trade-off is reduced capacity and lower spectral efficiency compared to urban settings. Comparative analysis shows a fundamental trade-off between coverage and capacity. While urban networks deliver superior data rates, rural deployments remain essential for bridging the digital divide. Energy efficiency and cost per user are critical considerations in rural areas, while spectrum efficiency dominates urban planning. Overall, 5G NR demonstrates strong adaptability, but deployment strategies must be tailored to the unique challenges of each environment. it is recommended to Prioritize energy-saving techniques (e.g., sleep modes, renewable-powered sites) in rural deployments to reduce operational costs. Strengthen rural backhaul infrastructure (e.g., fiber, microwave, or satellite integration) to support sustainable 5G coverage and Regulators and operators should align spectrum allocation, infrastructure funding, and innovation incentives to minimize the urban–rural performance gap.

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