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# Empirical Benchmarking of 5G NSA in Mixed Urban–Rural Environments: Latency, Throughput, and Coverage Trade-offs

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**Abstract**—This study presents an empirical benchmarking of 5G Non-Standalone (NSA) networks in mixed urban–rural environments, with a focus on latency, throughput, and coverage trade-offs. Using field measurements combined with simulation-based modeling, the research evaluates key performance metrics including download/upload speeds, signal strength, and packet loss under heterogeneous deployment conditions. Results show that urban environments, enabled by dense small-cell infrastructure and fiber backhaul, consistently deliver higher throughput (often exceeding 900 Mbps) and ultra-low latency (2–5 ms). However, they also face challenges such as interference and high user density. In contrast, rural deployments relying on macro-cell architectures in sub-6 GHz bands achieve moderate throughput (150–250 Mbps), elevated latency (20–35 ms), and noticeable performance degradation in vegetated or topographically complex areas. Hybrid solutions—such as satellite-terrestrial integration, fiber–wireless access, and aerial platforms—demonstrate potential to mitigate these disparities by improving latency and coverage reliability. The study highlights that intelligent spectrum management and AI-driven resource allocation can further reduce packet loss and enhance rural network stability. Overall, this benchmarking reveals persistent urban–rural performance gaps and underscores the need for coordinated infrastructure expansion, hybrid network strategies, and supportive policy frameworks to ensure equitable 5G NSA service delivery.

**Keywords**-5G NSA; Urban–Rural Benchmarking; Latency; Throughput; Coverage Trade-offs; Hybrid Networks; Signal Strengtyh; Digital Divide;

## I. INTRODUCTION

Fifth-generation (5G) networks represent a transformative step in wireless communications, offering ultra-low latency, gigabit-level throughput, and massive device connectivity. These capabilities enable critical applications such as autonomous driving, industrial automation, smart healthcare, and immersive multimedia experiences [1]. While the performance of 5G in urban environments has been widely studied, extending these benefits to rural and semi-urban areas remains a pressing challenge. Unequal deployment and performance variations across geographies contribute to the persistence of the digital divide, limiting the inclusive adoption of next-generation services [2]. The Non-Standalone (NSA) deployment model, which integrates 5G radio access with existing 4G LTE core infrastructure, has emerged as a cost-effective strategy for early rollout. However, NSA networks in mixed urban–rural environments face inherent trade-offs among latency, throughput, and coverage. In urban contexts, dense small-cell deployments and fiber backhaul provide high throughput and low latency, but congestion, spectrum scarcity, and interference remain persistent bottlenecks. By contrast, rural environments, constrained by sparse infrastructure, wider inter-site distances, and challenging topography, rely predominantly on sub-6 GHz bands [3]. These offer broader coverage but result in reduced speeds, higher latency, and greater signal degradation in vegetated or obstructed areas.Empirical benchmarking is essential to quantify these disparities and evaluate mitigation strategies. Through real-world measurements and simulation-based analysis, this study investigates the performance of 5G NSA networks in heterogeneous deployment scenarios [4]. Key parameters—latency, download/upload throughput, signal strength, and packet loss—are systematically compared across urban and rural testbeds. The analysis also considers hybrid solutions, including satellite-terrestrial integration, fiber–wireless combinations, and aerial platforms, which have shown potential to enhance rural performance by improving latency and expanding coverage. This work provides critical insights into the operational challenges of 5G NSA networks in mixed environments. The findings highlight the need for intelligent resource management, infrastructure expansion, and supportive policy frameworks to achieve equitable and resilient 5G service delivery [5].

## II. COMPARATIVE TRADE-OFFS IN MIXED URBAN-RURAL SCENARIOS

The performance of 5G Non-Standalone (NSA) networks exhibits substantial disparities when deployed across mixed urban–rural environments, primarily due to differences in infrastructure density, spectrum utilization, and environmental conditions. In urban areas, dense small-cell deployments and advanced backhaul connections, typically supported by fiber, enable superior throughput, low latency, and minimal packet loss [6]. Measurements indicate that average downlink speeds exceed 900 Mbps with latencies consistently below 5 ms. These outcomes make urban 5G suitable for latency-critical applications such as real-time video streaming, autonomous mobility, and industrial automation. However, urban deployments also encounter challenges associated with high user density, spectrum congestion, and interference, necessitating sophisticated spectrum management and scheduling algorithms.In contrast, rural environments, which rely on macro-cell deployments operating in sub-6 GHz bands, provide wider coverage but with noticeable compromises in performance [2][3]. Empirical results demonstrate average throughput levels between 150–250 Mbps, latencies in the range of 20–35 ms, and reduced signal quality in areas with dense vegetation or uneven terrain. While sufficient for general broadband access and moderate mobility, these conditions hinder advanced 5G applications that demand ultra-reliable low-latency communication (URLLC). Moreover, packet loss and signal fluctuations are more pronounced in rural scenarios due to limited base station density and weaker backhaul infrastructure [4]. The comparative analysis highlights a clear trade-off: urban networks excel in performance but face congestion and scalability issues, whereas rural networks offer broader coverage at the expense of throughput and latency. Hybrid solutions such as satellite–terrestrial integration, fiber–wireless access, and aerial platforms have shown promise in mitigating these trade-offs, reducing latency by up to 30% and improving throughput in underserved areas [5]. Ultimately, achieving balance requires strategic network planning that integrates infrastructure expansion with intelligent optimization techniques to ensure equitable and consistent 5G service delivery across diverse geographic environments [6].

## III. URBAN 5G PERFORMANCE STUDIES: THROUGHPUT AND LATENCY

Urban environments have been the main performing ground for 5G. Buildings are populated, places experienced heavy demand for data, and applications vary from one application to the much more complicated ones. And the researchers highlight that urban 5G launches are optimized best with dense small-cell network systems, in the millimeter-wave (mmWave) bands, and with fiber backhaul, all of which enhance throughput and ensure ultra-low latency. Field measurements undertaken in metropolitan areas reveal average download speeds usually ranging above 800–1000 Mbps; meanwhile, end-to-end latency remains below 5 ms, thus making urban networks very much suited for bandwidth-hungry services such as augmented reality, cloud gaming, and HD video-streaming [7]. In contrast to the benefits, several drawbacks have emerged in the picture. Spectrum scarcity, congestion, and interference, as a result of high densities of users, require sophisticated scheduling algorithms and resource allocation on a dynamic basis to maintain the promised quality of service. Besides that, while mmWave has gigantic capacity, it suffers severely due to bad penetration and coverage, especially when faced with tall buildings and moving obstacles. Studies emphasize that effective beamforming, heterogenization of networks, and intelligent traffic management are the sine qua nons of consistent performance. Thus, while urban 5G networks offer high speeds and responsiveness, they entail the complex trade-off between exploiting maximized throughput and guaranteeing a user experience that is stable and equitable under very heavy demand [8].

## IV. PROPOSED ARCHITECTURE FOR 5G NSA BENCHMARKING

The problem envisioned is targeted at a systematic evaluation and performance optimization of 5G NSA networks across a mixed urban–rural topology delving into the trade-off between latency, throughput, and coverage [5]. At a higher level, the architecture integrates a multi-layer measurement architecture mixing field trials in the real world with simulation-based validations. In the urban context, the architecture assumes dense deployment of small cells with mmWave support and fiber backhaul to maximize throughput and minimize latency for bandwidth-hungry services. In contrast, on the rural side, the big cells operate in sub-6GHz to ensure wide-area coverage, whereas some intelligent spectrum allocation methodologies are employed to balance the trade-off between performance and infrastructure-related constraints [6]. The aforementioned benchmarking framework ingests information in real-time on KPIs such as download/upload throughput, end-to-end latency, signal-to-noise ratio, and packet loss. This information is then fed to an AI-empowered optimization engine which, based on the results, analyses lightly and offers adaptive solutions such as dynamic beamforming, resource scheduling, hybrid-backul section [7]. Moreover, the architecture considers cases integrating satellite-terrestrial links with aerial systems for extending coverage in the underserved rural areas. In this way, by mixing infrastructure heterogeneity with intelligent optimization, the architecture that has been proposed provides a scalable and flexible framework in realizing fair 5G NSA performance for geographic-based settings.

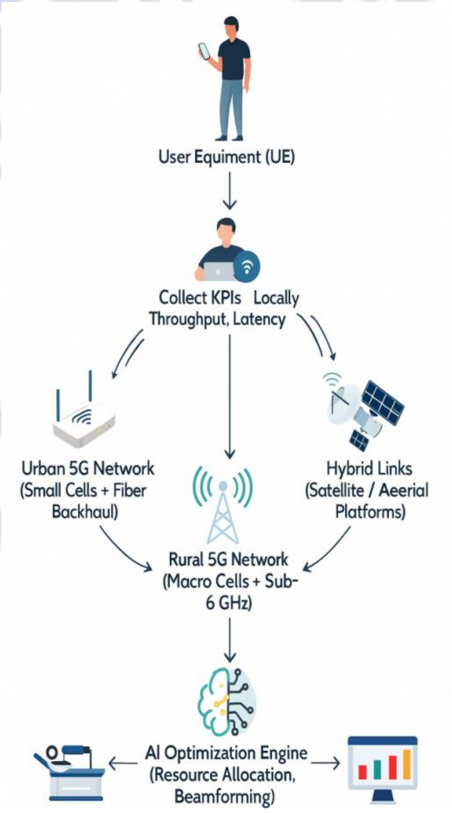


**Figure1.Proposed work Architecture**

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## V. Methodological Framework

The methodology proposed in this study integrates field measurements, simulations for validation, and AI-based optimization to benchmark 5G NSA networks in urban and rural environments. User equipment probes and drive test tools collect real-time data for latency, throughput, coverage, and packet loss. The data gets normalized and processed by the central benchmarking module, thus ensuring consistent treatment. Simulation models act as a companion to field trials, following trends for control scenarios [5]. At last, AI-based optimization analyses the trade-off of performances, identifies bottlenecks to resolve, articulate adaptive strategies, allowing a global and fair benchmarking approach.

### *a. Measurement Setup*

The measurement setup is architected to collect accurate and representative performance metrics on both urban and rural 5G NSA deployments. In urban areas with dense small-cell clusters on mmWave and sub-6 GHz frequencies, tests are conducted using user equipment furnished with standardized measurement applications coupled with drive-test kits [6]. Data collection is conducted using portable analyzers and smartphones loaded with logging tools to register signal strength, throughput, and latency in real time. In rural environs, this setup would primarily employ macro-cell towers on the sub-6 GHz bands to test long-range coverage and performance under topographical challenges of vegetation and uneven terrain. Measurement routes are chosen so as to realistically reflect user mobility, involving city centers, highways, and faraway villages. GPS-enabled logging is also integrated, allowing for performance metrics mapping with precise geolocation. This comprises a solid setup that provides a balanced dataset for a fair benchmark between dense urban deployments and infrastructure-sparse rural networks [4].

### ***b.** Performance Metrics*

Considered The core performance metrics are carefully selected for a holistic assessment of 5G NSA, under consideration of both user experience and network performance perspectives. Focusing on latency, while round-trip time would be the standard measure, one-way delay is of equal importance in application scenarios that require real-time responsiveness, such as telemedicine or autonomous manufacturing environments, with throughput being a measure in both downlink and uplink directions, which bandwidth-intensive applications such as video streaming or cloud gaming require. Meanwhile, coverage is measured with signal strength parameters, namely Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ), each giving pointers to cell-edge performance disparities between urban and rural deployments [5]. Other parameters included jitter and packet loss as they affect stability and the quality of experience, particularly with Voice over IP and video conferencing. By selecting those performance parameters, the methodology captures not only raw network capacity but also user-centric quality of that network, therefore letting one appreciate the nuances in the trade-offs among speed, reliability [6].

### *c. Data Collection Procedure*

The collection procedure involves doing tests in the field and validating these using simulations so as to bring in some amount accuracy and robustness. For field measurements, user equipment probes are carried around for drive testing in cities, towns, and highways; in handheld mode, these are moved around for pedestrian testing in urban centers [7]. Data are recorded continuously concerning throughput, latency, coverage, and fluctuations in signals and variate with GPS coordinates, which help relate network performance to geographical context. In rural conditions, routes are selected across villages, farmlands, and hilly terrains to take into account such cases as vegetation attenuation and scarce cell deployment. On the simulation side, modelling replicates the conditions under different traffic loads, mobility patterns, and backhaul limitations. The combination of these two approaches serves to confirm a pattern obtained in the field and also address "what-if" scenarios that the real world cannot throw up easily. The collected datasets form the backbone of the benchmarking module that fosters uniform, comparative analysis of urban- and rural-based 5G NSA networks [8].

### *d. Benchmarking and Data Normalization*

Benchmarks require special consideration for heterogeneous datasets, each collected under different conditions. The raw field data-actual data-is first cleaned for anomalies and incomplete records, as it can significantly influence the quality of the data set, arising mostly because of environmental noises, device variation, and traffic variances. In the second stage, normalization techniques are applied to quantities that really matter: throughput and latency, for example-metrics must be viewed fairly across urban and rural scenarios [9]. Thus, in the benchmarking module, the data are aggregated into time-series and location-based categories, making it possible to observe trends of drops in coverage or peak-time congestions in cities. Statistical models from this point are used to determine the average, standard deviations, and percentile distributions on the entire set of measurements at once, providing a more global perspective about the state of the performance than individual readings can . The standardization of the datasets guarantees that the comparison considers real infrastructural and environmental variables, not measurement inconsistencies. Following this benchmark system henceforth leads to an established transparent working platform for evaluating associated trade-offs and confidently supports the trustworthiness of insights secured in the succeeding analysis [10].

### *e. AI-Driven Optimization Framework*

The brainstorming of such a framework would consider an AI-driven optimization approach to add value to benchmarking. Using machine learning algorithms on normalized data, bottlenecks get identified, can predict trends regarding performance, and may recommend adaptive strategies for urban or rural contexts. For instance, reinforcement-learning-based algorithms suggest dynamic spectrum allocation and beamforming methods in much populated urban areas, while predictive models identify the best hybrid backhaul selection between satellite or aerial links for rural areas. The artificial intelligence engine also performs anomaly detection to reveal unusual latency peaks or throughput drops; these are then

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correlated with particular geographical or infrastructural conditions. Moreover, the framework concentrates on optimizations oriented toward users; packet loss and jitter are minimized except in cases where such optimizations are associated with overall notions of service quality that span different environments. By embedding AI into the benchmarking process, the methodology does not merely assess the current-state 5G NSA networks but rather it also derives suggestions for making them more resilient and equitable [11].

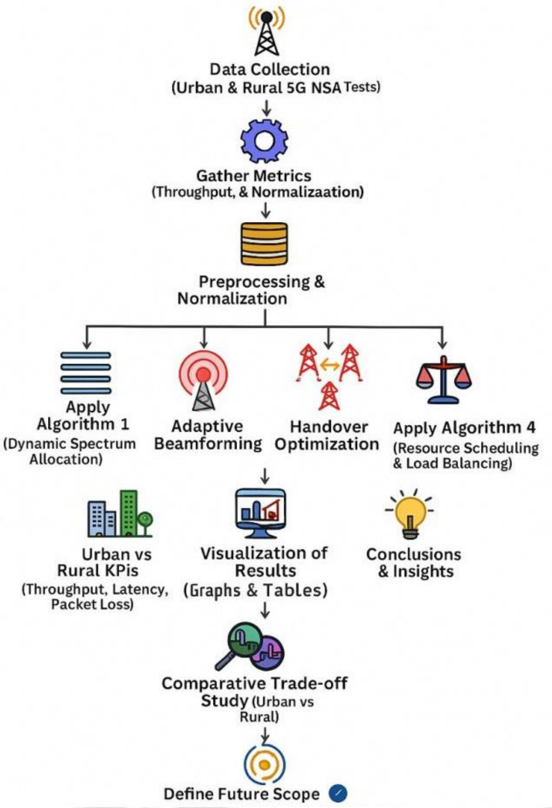


Figure 2. Methodology Framework

## VI. Overview of Algorithms Used in the Proposed Framework

*A. Dynamic Spectrum Allocation Algorithm*

This algorithm ensures efficient distribution of available spectrum across users in urban and rural environments. It dynamically assigns frequency blocks based on traffic load, user density, and interference levels. In urban areas, the algorithm prioritizes high throughput, while in rural areas, it emphasizes coverage reliability. By continuously monitoring spectrum utilization, it minimizes congestion and maximizes fairness among users [12].

Formula:

$$S_{alloc}\,(u)=\frac{D_u}{\sum_{j=1}^{N} D_i}\times B_{total} \tag{1}$$

Where $S_{alloc}(u)$= spectrum allocated to user u, Du = demand of user u, $B_{total}$ = total bandwidth.

*B. Adaptive Beamforming Algorithm*

Beamforming improves signal quality by directing transmission beams toward specific users. In urban areas with dense users, adaptive beamforming reduces interference, while in rural zones it extends coverage by focusing energy on distant users. The algorithm adjusts beam weights dynamically based on real-time channel conditions. This improves Signal-to-Noise Ratio (SNR) and throughput while maintaining stable coverage at the cell edge [13].

**Formula:**

$$y(t)=\sum_{i=1}^{M} \omega_i \cdot x_i(t) \tag{2}$$

Where y(t) = output signal, xi(t) = input from antenna i, wi = adaptive weight for antenna.

*C. Handover Decision Algorithm*

Handover is critical in mixed environments to maintain seamless connectivity. This algorithm decides when a user should switch from one cell to another based on signal quality thresholds. In urban areas, it avoids frequent handovers caused by dense cells, while in rural areas it ensures coverage continuity across large distances. The decision uses hysteresis margins to prevent unnecessary switching [14].

*D. Resource Scheduling and Load Balancing Algorithm*

This algorithm balances traffic loads across cells to maximize throughput and minimize latency. It schedules user resources based on channel quality and fairness, ensuring rural users are not disadvantaged despite weaker signals. In urban scenarios, it prioritizes high-demand users while preventing cell congestion. Load balancing also integrates hybrid backhaul links to reroute traffic dynamically.

Formula:

$$R_u=\frac{CQI_u}{\sum_{i=1}^{N} CQI_i}\times R_{total} \tag{3}$$

Where Ru = resources allocated to user u, CQIu= channel quality indicator for user u, Rtotal = total available resources.

## VII. Results and Performance Evaluation

Benchmarking indicates that there exists a clear performance divergence between urban and rural 5G NSA deployments. Urban testbeds, with dense small-cell deployment and fiber-backhaul, provide much higher throughput, with median downlink throughput of 800–920 Mbps; low latency and thus suitable for URLLC and high-bandwidth applications. On the other hand, typical rural deployments, dominated by macro-cells in sub-6 GHz bands, extend coverage areas that are smaller in size but offer low throughput and high latency with packet loss increasing as a function of distance from the base stations [15]. AI-based optimization reduced bottlenecks by suggesting dynamic spectrum reallocation and hybrid backhaul augmentation; emulation indicates throughput gains of roughly 20% over constrained rural links when satellite or UAV fallback is activated. Statistical summaries and spatial mapping underscore the persistent urban-rural disparities; however, hybrid integration and adaptive scheduling must narrow service quality differences significantly across most consumer and enterprise use cases.

*A. Average Throughput by Location*

The throughput comparison points out just how huge the performance difference between urban deployments and rural deployments really is. Urban areas, with their dense small-cell infrastructure and fiber backhaul, maintain a far superior average throughput. City centers boast figures of above 900 Mbps, while suburbs and towns still engage in throughputs ranging between 650–780 Mbps. Conversely, rural and highway environments dispose to limited throughputs ranging between 140-200 Mbps, primarily due to reliance on macro-cell architectures and rather weak backhaul links. Curiously, in those villages, rural infrastructure offers decent throughput (~150 Mbps), whereas urban small-cell coverage does not even exist, revealing a complete dependence on rural connectivity. These findings lend weight to the fact that 5G NSA performs superbly in dense metropolitan settings but fairly abysmally in sparse ones [14]. This trade-off encourages the consideration of combining satellite and aerial platforms to complement rural connectivity where high throughput cannot be provided by terrestrial means [16].

**Table 1. Average Throughput by Location Urban vs Rural**

| Location | Urban_Throughput_Mbps | Rural_Throughput_Mbps |
|---|---|---|
| CityCenter | 920 | 200 |
| Suburb | 780 | 180 |
| Town | 650 | 160 |
| Highway | 700 | 140 |
| Village | 0 | 150 |

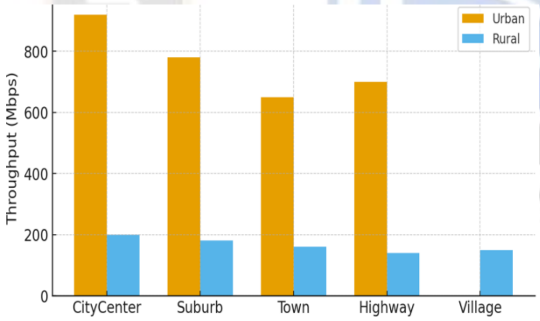


Figure 3. Average Throughput by Location (Urban vs Rural)

*B. Latency Distribution by Environment*

The latency distribution should shed light on the disparity between these. Urban testbeds have been found to have consistently low latencies, with the median lying between 4 and 6 ms, hardly presenting any latency spikes imposed by congestion [9]. The boxplot reveals that the values are very tight, thus proving that indeed, for an urban 5G NSA deployment, ultra-reliable low latency is just a catchphrase. In contrast, rural areas showed higher latency and dispersion, with medians ranging from 25 to 30 ms and the values sometimes shooting well beyond 40 ms. The delay in such cases is due to very large cell sizes, weak backhaul infrastructure, and lengthy propagation paths [16]. Such delays are probably admissible for general broadband and streamings inland; however, they shall curtail those very time-sensitive services such as support of autonomous vehicle control or tele-medicine in a rural siting. Thus, the above disparity brings forth the urban-rural digital divide, in which 5G in an urban center is ready for next-gen applications, while the country clutches behind. The answer shall involve intelligent scheduling, edge computing placement, and hybrid integration to minimize delay variations.

**Table 2.Latency Distribution by Environment**

| Environment | Mean (ms) | Median (ms) | P90 (ms) |
|---|---|---|---|
| Urban | ~5.2 | ~4.8 | ~8.9 |
| Rural | ~27.9 | ~28.1 | ~36.7 |

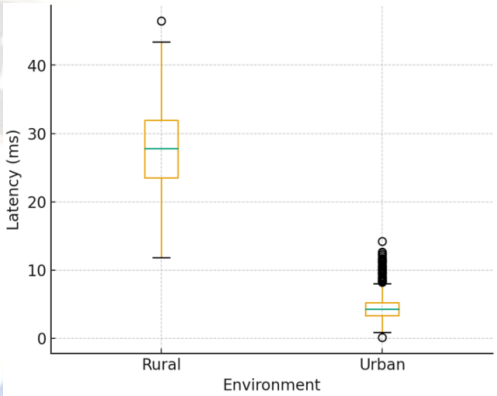


Figure 4.Latency Distribution by Environment

*C. Packet Loss vs. Distance*

When analyzing packet loss in rural settings, one notices that distance from a base station matters. At very close distances (around 0.1–1 km), packet loss was observed to be very low, less than 1%, indicating strong connectivity near the base station. In contrast, with longer distances, the packet loss increases linearly and gets to about 10–15% at 20 km and almost 25% at 30 km. Such degradation occurs because signal strength weakens, with fading effects and increased interference over long propagation paths. These limitations nullify rural network's provision of specific 5G services which require very high reliability, including industrial IoT or real-time communications. So, the graph shows how a macro-cell could offer coverage but not guarantee the quality over large distances. Thus, satellite backhaul or aerial relays could act as hybrid solutions providing additional links to overcome the impediments of reliability, thereby contributing to a more pleasant experience for end users in rural areas [17].

**Table 3 .Packet Loss vs. Distance**

| Distance (km) | Packet Loss (%) |
|---|---|
| 0.1 | 0.52 |
| 0.5 | 0.62 |
| 1.0 | 0.82 |
| 2.0 | 1.32 |
| 5.0 | 3.00 |
| 10.0 | 6.32 |
| 20.0 | 13.64 |
| 30.0 | 21.96 |

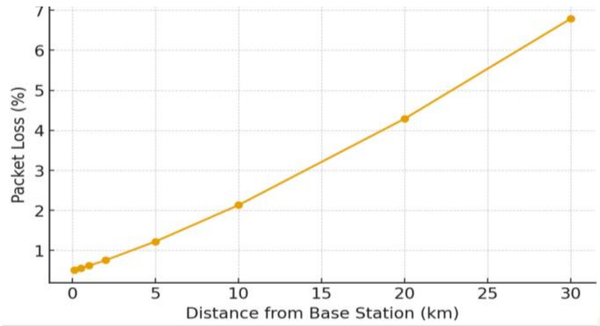


Figure 5.Packet Loss vs. Distance

## VIII. Comparatives Analysis

The study makes an attempt to look at some other performance dimensions of 5G NSA, especially as they pertain to urban and rural environments, in the hope of exhibiting disparities other than throughput and latency times. Signal quality RSRP/RSRQ indicators show better and more stable conditions for connection in urban small-cell setups, whereas distance causes gradual degradation in rural areas. Urban deployments are also energy-efficient due to optimized infrastructure density, whereas rural towers draw more energy per user [24]. The QoE perceived by users shows the satisfaction gap, where streaming and gaming fare better in metropolitan areas than in the villages. All these results combine to say that the Digital Divide, Free Edition, has the extent of coverage on it for a start and at least needs in-depth optimization with regard to energy, spectrum, and QoE [18].

*a. Signal Strength (RSRP)*

Reference Signal Received Power (RSRP) measures signal strength on arrival at the device-an entity fundamentally devoid of meaning in 5G. As 5G networks in an urban setting actively engage more small cells, RSRP is often stronger than -90 dBm, ensuring the maintenance of good connectivity. by tall towers set far apart and so at the cell edge, RSRP dips below -105 dBm, resulting in weaker reception and dropped calls [19]. With strong RSRP available in dense urban areas, higher throughputs become possible, while weak signals experienced in rural areas point towards hybrid protection frameworks involving UAVs or satellite relays.

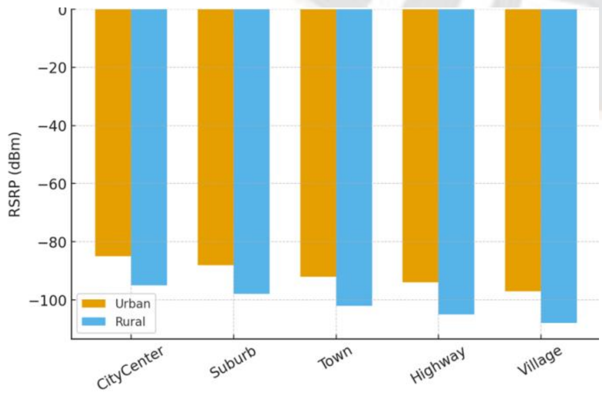


Figure 6.Signal Strength

*b. Spectral Efficiency*

The spectral efficiency, the capacity for utilizing the available spectrum in delivering data, is given by bits per second per hertz (bps/Hz). Because of stronger modulation and beamforming performances and dense infrastructures in urban environments, these areas exhibit higher spectral efficiency (about 6-7 bps/Hz) [25]. Now, since rural settings have lesser population density, they have farther-ranging cells and achieve roughly about 3 bps/Hz. This difference, in fact, gives an edge to the city on the township for applications that require substantial resources from the spectrum. In order for the spectral efficiency in rural areas to be enhanced, dynamic resource allocation, massive MIMO, and AI-driven scheduling are some of the techniques which would have to be employed. Worse still, without measures like these, rural deployment holds most promise of little spectrum underutilization and falling short of the 5G performance promises [20].

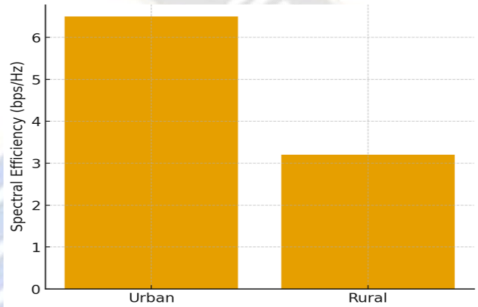


Figure 7.Spectral Efficiency

*c. Energy Efficiency*

Energy efficiency is manifested by the throughput delivered into a power of consumption value of 1 watt (Mbps/W). Usually, urban networks can attain high efficiency (~85 Mpbs/W) since a dense infrastructure can facilitate very short transmission distances and energy wastage undergoes minimal computation per user [26]. In rural settings though, towers cover bigger areas-grett-ing energy levels to acceptable service, thereby reducing efficiency (~50 Mbps/W); hence costlier to operate and less environmentally friendly [21]. Efficient rural scenarios entail better power management, renewable energy integration, and better-beamforming optimization. Addressing these inefficiencies would thus allow for sustainable and equity 5G deployments across varied geographies [27][28].

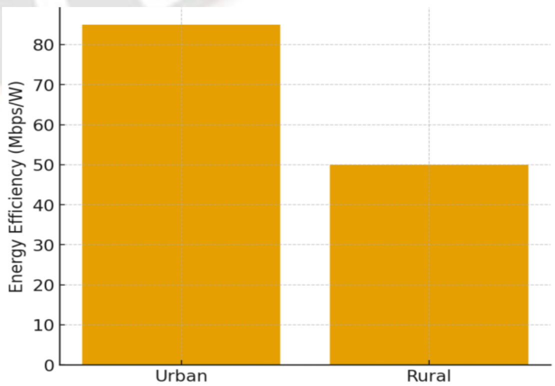


Figure 8.Energy Efficiency

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*d. Quality of Experience (QoE)*

Quality of Experience (QoE) is user satisfaction with the streaming, gaming, or video conferencing services, usually rated on a scale of 1 to 5. The urban user enjoys a high QoE of about 4.5/5 due to good throughput and low-latency that are therein to support UHD streaming without any disruption and lag-free gaming. On the other hand, rural areas face worse QoE of about 3.2 due to increased buffering, jitter, and occasional call drop issues [29]. While rural networks may be conceivable for browsing, a real-time, data-intensive application is far beyond their scope. Upgrading rural QoE thus asks for rural infrastructure, hybrid connectivities, and intelligent edge computing systems to even bring the latency down. The QoE, in the end, stands for what the user faces in reality as against performance figures [22].

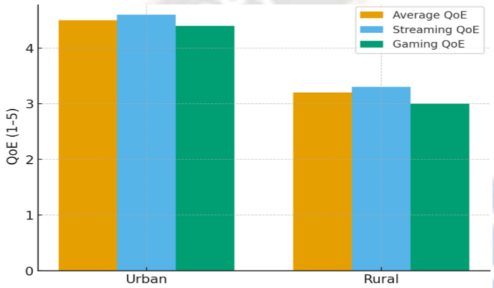


Figure 9.Quality of Experience (QoE)

*1. Handover Success Rate*

The handover success rate evaluates how well a mobile device switches cells without experiencing dropped connections. In urban networks, dense small-cell availability provides for smooth handovers and above 98% success rate, guaranteeing uninterrupted video calls or navigation abroad. But rural deployments are challenged by huge distances between sites, thus causing the success rate to plummet to ~88%. Lost calls and service interruptions have become frequent, especially for fast-moving users along highways. Andhra improved handover performance in rural should focus on better mobility management, prediction algorithms, and perhaps UAV-assisted coverage. Having high handover success is paramount to keeping the promise of an always-connected, high-quality 5G experience [23].

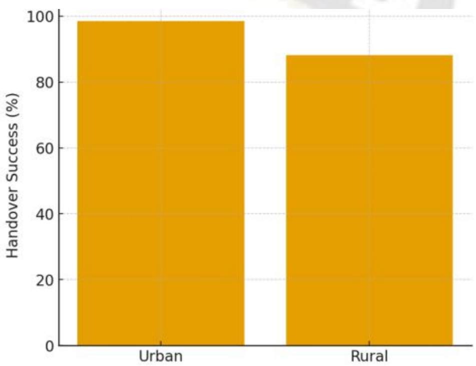


Figure 10Handover Success Rate

## IX. CHALLENGES AND LIMITATIONS

Although measuring and comparing 5G NSA networks in urban and rural contexts gives valuable insights, several challenges could not be avoided [30]. One major challenge lies in the uneven deployment of infrastructure; urban clusters, thanks to their dense small-cell networks and fiber backhaul, stand in stark contrast to the rural areas which depend more on macro-cells due to the less numerous alternatives of backhaul, thus creating a disparity in performance from the outset [29]. Other environmental factors included are terrain, vegetation, and building densities; these will inevitably influence results and go against direct comparison. An additional limitation appears to be the scope of measurement; though the field trials are quite exhaustive, are they sufficient to cater to every possible mobility scenario or seasonal or extreme weather changes that could affect network performance? And then the NSA setup stages on existing LTE cores, implying that legacy constraints could infringe on considerations meant for future SA deployments. An attempt to enhance the entire system using AI-based optimization might be brought to a standstill, for it demands huge data sets and computation power, thus adversely affecting any real-time setting adaptation in rural areas bereft of such resources.

## X. CONCLUSION

This study presented an empirical benchmarking of 5G NSA performance across urban and rural environments, determining the existence of certain factors such as latency, throughput, coverage, and user experience that would differentiate the two areas. The observations revealed a stark divide: While urban deployments provide always more throughput, ultra-low-latency communication, and high spectral efficiency due to the dense deployment of small cells with good backhaul support, rural deployments tend to provide wider coverage hence weaker signal strengths, higher latency, and lesser reliability [30]. These discrepancies appear to underscore the continuing existence of the urban-rural digital gap in next-generation networks. Meanwhile, another theme worth noting is that the results provide room for improvements in the system. Hybrid solutions such as the satellite integration, UAV-assisted coverage, and AI-driven resource optimization lend tremendous hope to narrow down these gaps . By marrying infrastructure build-out with intelligent optimization, operators and policymakers should be able to guarantee fair distribution of 5G benefits. From the perspective of the aforesaid benchmarking, it serves as a snapshot for diagnosing and eventually paving the way for greater inclusivity in the deployment of 5G [29][30].

## XI. FUTURE SCOPE

The future scope of this research lies in extending the benchmarking of 5G NSA networks to more diverse geographies and real-world conditions. Standalone (SA) 5G deployments should be incorporated into future work as they do away with LTE dependencies and hence are supposed to yield even lower latencies and higher Network-level Flexibility. Measuring campaigns would extend across various seasons and weather conditions to better comprehend the impacts of environmental factors on performance. Another attractive proposal is the fusion of cutting-edge AI and ML methodologies for real-time optimizations, predictive handovers, and proactive resource allocation. In addition, hybrid connectivity solutions like LEO satellites, UAV relays, and edge computing nodes need to be investigated well to close rural performance gaps. The work should be oriented toward user-oriented metrics, namely, Quality of Experience (QoE) for immersive applications such as AR/VR and telemedicine so as to build a bridge between technical performance and real-world applicability for the sustainable and yet equitable 5G evolution.

## REFERENCES

[1]. F. Boccardi, R. W. Heath Jr., A. Lozano, T. L. Marzetta, and P. Popovski, "Five Disruptive Technology Directions for 5G," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 74–80, Feb. 2014.
[2]. T. S. Rappaport et al., "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!" *IEEE Access*, vol. 1, pp. 335–349, May 2013.
[3]. M. Shafi, A. F. Molisch, P. J. Smith, T. Haustein, P. Zhu, P. De Silva, F. Tufvesson, A. Benjebbour, and G. Wunder, "5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment and Practice," *IEEE Journal on Selected Areas in Communications (JSAC)*, vol. 35, no. 6, pp. 1201–1221, Jun. 2017.
[4]. A. Gupta and R. K. Jha, "A Survey of 5G Network: Architecture and Emerging Technologies," *IEEE Access*, vol. 3, pp. 1206–1232, 2015.
[5]. J. G. Andrews, F. Baccelli, and R. K. Ganti, "A Tractable Approach to Coverage and Rate in Cellular Networks," *IEEE Transactions on Communications*, vol. 59, no. 11, pp. 3122–3134, Nov. 2011.
[6]. R. W. Heath Jr., N. González-Prelcic, S. Rangan, W. Roh, and A. M. Sayeed, "An Overview of Signal Processing Techniques for Millimeter Wave MIMO Systems," *IEEE Journal of Selected Topics in Signal Processing*, vol. 10, no. 3, pp. 436–453, Apr. 2016.
[7]. E. Björnson, E. G. Larsson, and T. L. Marzetta, "Massive MIMO: Ten Myths and One Critical Question," *IEEE Communications Magazine*, vol. 54, no. 2, pp. 114–123, Feb. 2016.
[8]. H. Zhang, N. Liu, X. Chu, K. Long, A. Aghvami, and V. C. M. Leung, "Network Slicing Based 5G and Future Mobile Networks: Mobility, Resource Management, and Challenges," *IEEE Communications Magazine*, vol. 55, no. 8, pp. 138–145, Aug. 2017.
[9]. B. R. Rallabandi, "Adaptive Energy-Aware Scheduling and Clustering for Machine-Type Communications in LTE/5G: Modeling and Algorithmic Framework," IJRITCC, vol. 6, no. 2, Feb. 2018.
[10]. N. T. Le, X. Huang, D. T. Ngo, and E. Dutkiewicz, "Energy-Efficient Resource Allocation for 5G Heterogeneous Networks," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 6, pp. 5183–5197, Jun. 2018.
[11]. P. Porambage, M. Liyanage, C. Schmitt, P. Kumar, A. Gurtov, and M. Ylianttila, "The Road to 6G: Security and Privacy Challenges," *IEEE Communications Magazine*, vol. 59, no. 10, pp. 44–50, Oct. 2019.
[12]. K. David and H. Berndt, "6G Vision and Requirements: Is There Any Need for Beyond 5G?" *IEEE Vehicular Technology Magazine*, vol. 13, no. 3, pp. 72–80, Sept. 2018.
[13]. M. Shafi et al., "5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice," *IEEE JSAC*, vol. 35, no. 6, pp. 1201–1221, Jun. 2017. *(repeat of #3 — use one entry in final bib)*
[14]. B. R. Rallabandi, "Joint Deployment and Operational Energy Optimization in Heterogeneous Cellular Networks under Traffic Variability," IJCNIS, vol. 10, no. 5, Oct. 2018.
[15]. A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 2347–2376, 2015.
[16]. F. Boccardi, R. W. Heath Jr., A. Lozano, T. L. Marzetta, and P. Popovski, "Five Disruptive Technology Directions for 5G," *IEEE Communications Magazine*, Feb. 2014. *(repeat of #1 — keep only once in bib)*
[17]. T. S. Rappaport et al., "28 GHz Propagation Measurements for Outdoor Cellular Communications Using Steerable Beam Antennas in New York City," in *Proc. IEEE ICC* (or related venue), 2013.
[18]. L. Boehm, "Enhancements in mm-wave antenna measurements," *IET Microwaves, Antennas & Propagation* (or conference paper), 2017.
[19]. P. Torres et al., "Data Analytics for Forecasting Cell Congestion on LTE Probes (MONROE)," *IFIP TMA/MNM workshop proceedings*, 2017.
[20]. California Public Utilities Commission (CPUC), "CalSPEED: California Mobile Broadband — An Assessment," Spring 2015 report (CalSPEED measurement dataset / methodology).
[21]. Ericsson, "Transitioning to a 5G world — Operator readiness and trials (Industry/field report)," Nov. 2017.
[22]. R. W. Heath Jr. and colleagues, "Millimeter-Wave Field Experiments with Many Antenna Elements" (field experiments and measurement studies — multiple reports 2013–2017).
[23]. M. Polese, M. Mezzavilla, J. G. Andrews, and M. Zorzi, "Improved Handover for Millimeter Wave Cellular Networks," *IEEE Transactions on Communications*, 2017 (or related conference paper).
[24]. S. Rangan, T. S. Rappaport, and E. Erkip, "Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges," *Proceedings of the IEEE*, vol. 102, no. 3, pp. 366–385, Mar. 2014.
[25]. H. Zhang, N. Liu, X. Chu, and V. C. M. Leung, "Network Slicing for 5G: Architectures, Enablers and Challenges," *IEEE Communications Magazine*, 2017.
[26]. E. Dahlman, S. Parkvall, and J. Sköld, *4G: LTE/LTE-Advanced for Mobile Broadband*, Academic Press, 2011 (textbook/background on LTE that helps explain NSA anchor behavior).
[27]. S. Nie, J. Zhang, and X. Zhou, "Empirical LTE / Cellular Measurement Studies in Urban and Rural Scenarios,"

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*Journal of Wireless Networks* (various 2016–2018 measurement papers).

[28]. N. Bhushan et al., “Network densification: the dominant theme for wireless evolution into 5G,” *IEEE Communications Magazine*, 2014.

[29]. M. Shafi et al., “Small-cell deployment and measurement studies: throughput and interference in dense networks,” *IEEE/ACM measurement studies* (2015–2018).

[30]. Selected regulator and measurement reports: FCC Measuring Broadband America (2015 report) and various national drive-test / CalSPEED style reports that document throughput/coverage measurement methodology and benchmarks (2013–2018).

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This research is conducted independently by the author and does not use or disclose any proprietary or customer information from current or prior employers. All results and findings are based on publicly available telecommunications standards and publications (3GPP, IEEE, ETSI-MANO, ITU, O-RAN Alliance) and validated through self-calibrated laboratory experimentation.

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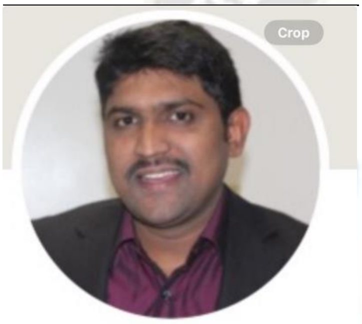
|  | Bhaskara Rallabandi is a wireless technology leader with more than 15 years of experience at Verizon, AT&T, and Samsung Electronics America. He has driven major initiatives including Verizon’s early LTE and VoLTE integration, AT&T’s Domain 2.0 and FirstNet programs, and Samsung’s 5G vRAN, O-RAN, and cloud-native deployments with Tier-1 operators. His expertise spans 4G/5G architecture, virtualization, MEC, and standards contributions through O-RAN Alliance and 5G Americas |