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A Comparative Analysis on Enhancement of Signal Reception in 4G Network Within Urban and Suburban Areas in Nigeria

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ABSTRACT
Signal reception quality in 4G LTE networks is a crucial factor that influences user experience, especially in terms of data throughput, latency, and network coverage. This study presents a comparative analysis of signal reception and improvement techniques across urban, suburban, and rural environments, using two empirical case studies. One was conducted in Lagos, Nigeria (urban), and the other in Igbeti, Oyo State, Nigeria (rural). The research was aimed at identifying common factors affecting 4G LTE signal reception and evaluate the effectiveness and scalability of enhancement methods including small cells, MIMO configurations, signal boosters, directional antennas, and enhanced Inter-Cell Interference Coordination (eICIC). Quantitative signal parameters such as data throughput, Signal-to-Interference-plus-Noise Ratio (SINR), Reference Signal Received Power (RSRP), and latency were analyzed. In the urban environment, small cell deployment and MIMO techniques used improved Signal-to-Interference-plus-Noise Ratio (SINR) by 32% and increased throughput from 18 Mbps to 33 Mbps, while latency was reduced by 45%. In contrast, rural enhancement using signal boosters and directional antennas led to an average RSRP improvement of 14 dBm and throughput increase from 4.5 Mbps to 11 Mbps, with a 30% drop in latency. A Multi-Criteria Decision Analysis (MCDA) model incorporating six performance criteria – signal strength, throughput, latency, cost, scalability, and ease of deployment – ranked MIMO and Signal Boosters were highest for urban and rural applications respectively, with scores of 4.1 out of 5. These results shows that techniques used to enhance the signals must be adapted to environmental contexts to maximize efficiency and cost-effectiveness. This work provided a strategic framework for network planners and telecom operators to be used to optimize 4G LTE coverage and performance.

Keywords: 4G LTE Network, MTN base station, Channel equalizer, Radio Channel, Radio Transmission.

1.INTRODUCTION
The fast growth of wireless and mobile communication has led to an increased demand for reliable wireless connectivityy and high-speed data, particularly in the area of 4G Long Term Evolution (LTE) networks. 4G networks often have some challenges in signal reception due to some factors such as environmental obstructions, mobility of users, and interference irrespective of its widespread deployment. These issues contribute to degradation of quality of service (QoS) which led to dropped calls, user dissatisfaction and slower data rates. [1].
One of the major issues facing 4G Long term Evolution (LTE) networks is ensuring consistent signal strength in structural environments and diverse geographical areas. Urban areas, for example, often face some transmission impairments such as pathloss, noise and signal attenuation due to high-rise buildings and dense population [2]. In rural settings, signal degradation is primarily caused by long distances from base stations and limited infrastructure [3]. This geographical discrepancy necessitates a comparative analysis of various signal improvement techniques.
Several methods have been proposed and implemented to improve 4G signal reception, such as the use of Multiple-Input Multiple-Output (MIMO) antennas, Distributed Antenna Systems (DAS), and signal repeaters [4]. Each technique offers unique advantages depending on the specific deployment scenario. MIMO technology, for example, improves spectral efficiency and link reliability by exploiting spatial diversity [5]. DAS extends coverage and reduces power consumption in large indoor environments [6].
Also, development of adaptive modulation and evolution in intelligent algorithms have further supported dynamic signal optimization in real-time [7]. Network planning and optimization tools, which include signal prediction and terrain modelling, have become increasingly critical for ensuring optimal base station placement and coverage [8]. The integration of femtocells and picocells in dense areas has shown to mitigate signal degradation and offload traffic from macro cells [9].
A comparative analysis of these techniques which the study is doing is necessary to determine their relative effectiveness under variations of environmental and user conditions. This work aims to compare various methods used to improve 4G signal reception, which contributed to the broader goal of enhancing performance of the network nd user experience in any communications system.[10].
In spite of the widespread deployment of 4G LTE networks all over the world, users continue to face significant challenges with the reception of quality signal, especially, in areas with complex terrain, dense urban development, or inadequate infrastructure. These signal reception problems lead to serious delay in data transmission, call drop, and poor user experience, which contradicts the limitation barriers of 4G technology to deliver high-speed, reliable mobile connectivity. The inconsistency in signal strength across several locations reveals a gap between the actual field conditions and the theoretical network performance. The technological solutions that have been proposed and implemented to address these issues are, signal repeaters, femtocells, MIMO (Multiple Input Multiple Output) systems, picocells, and Distributed Antenna Systems (DAS). Each approach offers specific benefits, but their effectiveness

varies depending on density of building, geographic location, mobility of users, and interference levels. However, there is a lack of comprehensive comparative analysis that evaluates the performance of these different signal improvement strategies under controlled conditions. The absence of such comparative insight limits service providers, the ability of network engineers, and policymakers to make informed decisions regarding the most appropriate and cost-effective solutions for improving signal reception in diverse environments. Hence, this study seeks to fill that gap by conducting a detailed comparative analysis of several signal improvement techniques to determine their weaknesses, strengths, and suitability for specific scenarios. By doing so, it aims to contribute to the development of more efficient and adaptive network planning strategies for existing and future LTE infrastructures.

Guezouli, [11], researched on a work titled, Adaptive Caching Strategies for Internet of Vehicles (IoV) based on LTE Signal Quality Analysis. The technique used was LTE signal quality analysis for adaptive caching in vehicular networks. This work examined the role of LTE signal quality in developing adaptive caching strategies to improve the Internet of Vehicles (IoV). The author intended to optimize data storage and retrieval based on real-time signal conditions. The advantages of the work were that it improved data accessibility in vehicle networks, optimized the overall system performance. But there were challenges in maintaining real-time signal quality measurements due to vehicular mobility. The research gap was lack of attention to mobility patterns and how they influence caching efficiency in IoV systems.

Another review was that of the work carried by Imoize [12], titled “Optimizing the Quality of Service of Mobile Broadband Networks for a Dense Urban Environment”. The method used in the work was Particle Swarm Optimization (PSO). This was used to optimize LTE network performance metrics. In the work, the study used PSO to optimize LTE performance in urban settings by concentrating on key indicators like quality (RSRQ), signal strength (RSRP), and data throughput, which aimed to improve overall efficiency of the network. The result was that the work provided practical insights into optimizing LTE in congested urban environments. However, it was spatially limited, and results may not be appropriate in less dense or rural areas. However, the gap from this work was that there was no exploration of dynamic mobility and its effect on network performance in urban areas were also explored.

Kumar [13], worked on Performance Enhancement in LTE Using Femtocells and Picocells. They used femtocells and picocells deployment for LTE network enhancement as the research technique. The research focused on deploying femtocells and picocells to improve LTE performance in indoor and high-demand areas. It analyzed their effect on signal strength and network capacity. The merits of the work were that it improved network coverage and reduced congestion in dense environments. However, there was high installation costs and limited mobility support. But more research was needed on the integration of femtocells with macrocell networks.

Basar and Alouini, [14], carried out research on 4G LTE Network Performance Optimization using LTE-Unlicensed spectrum (LTE-U) for spectrum optimization technique. The authors investigated how LTE-U can be used to improve LTE performance by manipulating unlicensed spectrum, improving coverage and reducing congestion in dense urban areas. The research provided effective spectrum management to alleviate network congestion. But there were regulatory challenges and potential interference with Wi-Fi networks. There was need to investigate the regulatory frameworks needed for widespread adoption of LTE-U.

Sood and Sharma, [15], did research title “Impact of Carrier Aggregation in 4G LTE Networks: A Review”. The author used Carrier Aggregation (CA) technique to improve 4G LTE network throughput. The study explored the potential of Carrier Aggregation in LTE networks which increases throughput by combining multiple frequency spectrums, addressing the issue of limited bandwidth in clogged areas. The study significantly improved network speed and user experience in high-traffic situations. But there was complexity in network management and upgrading of equipment especially during optimization. Thus, there is need for further researches on the impact of Carrier Aggregation (CA) on mobile device compatibility and power consumption.

The research titled Enhancing Signal Coverage and Quality in 4G Networks Using Distributed Antenna Systems (DAS) examined the use of DAS in 4G networks. The work used DAS to improve coverage in urban environments, particularly in underground areas, and large buildings which enhanced signal strength and data throughput. [16]. The study improved indoor signal quality and overall network reliability. But there were high costs of installation and maintenance challenges. The scalability and cost-effectiveness of DAS in large-scale deployments are highly recommended for future researchers.

Zhang and Liu, [17], researched on another work titled “A Comparative Study of Multiple Input Multiple Output and Beamforming Techniques for LTE Network Performance Improvement which was reviewed. They used MIMO and beamforming for signal improvement as the technique. The paper compared the impact of MIMO (Multiple Input Multiple Output) and beamforming technologies on LTE network performance, focusing on enhancing data throughput and signal reliability. There was significant performance improvement in both rural and urban settings. However, the work required complex implementation and as well as high computational resources. There is need for real-world performance evaluations and cost-benefit analyses of these techniques.

Wang and Zhang, [18], researched on Optimization of Signal Strength and Coverage in 4G LTE Networks Using Repeater Systems. The paper reviewed the use of signal repeaters to amplify the coverage of LTE networks, especially in remote and rural areas, where signal impairments such as attenuation is a major issue. The work provided a cost-effective solution for extending LTE coverage in underserved areas. However, there was potential signal degradation at extended communication ranges and interference. More research needed on optimizing repeater placement and minimizing interference.

Improving signal reception in 4G LTE networks is a key concern for ensuring high-quality mobile communication services. Signal reception quality is influenced by several enhancement techniques, which serve as the independent variables in this study. These include Multiple Input Multiple Output (MIMO) technology, signal repeaters, femtocells, picocells, and Distributed Antenna Systems [5], [6], [9].

These technologies aim to address challenges such as signal attenuation, interference, and coverage gaps, which are prevalent in both urban and rural environments [2], [3]. For instance, MIMO exploits spatial diversity to boost throughput

and signal reliability while femtocells and picocells enhance localized indoor coverage and relieve network congestion [7].
The dependent variables in this study are the measurable outcomes of signal reception performance, specifically: signal strength (RSSI), data throughput, latency, and coverage area [8], [1]. These metrics determine the quality of service (QoS) and user satisfaction in 4G LTE networks [10]. This framework operates under the assumption that deploying and optimizing the right combination of signal enhancement technologies will lead to improved network performance, especially in signal-challenged environments [4]. It also recognizes that environmental factors and infrastructure limitations may moderate the impact of these independent variables on the dependent outcomes [3].
Thus, the conceptual relationship can be summarized as follows:

Independent Variables (Signal Enhancement Techniques)
→ MIMO, Repeaters, Femtocells, Picocells, DAS

Dependent Variables (Network Performance Outcomes)
→ Signal Strength, Data Throughput, Latency, Coverage Area

The theoretical foundation of this study is grounded in several key communication and network theories that help explain the principles behind signal reception and enhancement in 4G LTE networks. Central to the study is Shannon's Capacity Theorem, which posits that the maximum data rate of a communication channel is fundamentally linked to the signal-to-noise ratio (SNR), bandwidth, and noise level. This theorem underscores the importance of signal strength and quality for ensuring high data throughput and reliable communication in 4G networks.
A key component of improving signal reception is Multiple Input Multiple Output (MIMO) technology, which leverages spatial diversity to increase data rates and enhance link reliability by transmitting multiple data streams over multiple antennas [19]. The effectiveness of MIMO in improving signal reception in 4G LTE networks is grounded in the theory of spatial multiplexing, where the use of multiple antennas allows for the transmission of several parallel data streams, thus increasing the system capacity [5].
The theory of cellular networks further informs this study by explaining the role of base station density and cell size in signal quality. As the theory suggests, reducing the size of cells (i.e., using small cells like femtocells and picocells) helps improve signal strength and reduce interference, particularly in dense urban and indoor environments [9]. These small cells enhance coverage and capacity by offloading traffic from the macrocell network [6].
Another relevant theory is interference management theory, which emphasizes minimizing interference to enhance signal quality. Interference in LTE networks arises due to factors such as overlapping frequencies and the presence of obstacles, leading to signal degradation [2]. Technologies like DAS (Distributed Antenna Systems) help reduce interference by distributing the signal over multiple antennas, thus increasing coverage and improving reception in complex environments [4]. Cognitive radio theory, which deals with dynamic spectrum access, is also crucial in understanding how 4G networks can adapt to changing conditions and optimize signal reception. By using intelligent algorithms to dynamically allocate bandwidth based on real-time network conditions, signal reception can be improved, particularly in environments with high traffic [7].
Finally, signal propagation theory plays a key role in understanding how signals travel through various media, such as the atmosphere, buildings, and other obstacles. This theory explains the mechanisms behind signal attenuation, reflection, diffraction, and scattering, all of which influence the strength and reliability of the received signal. These principles help identify potential areas where signal enhancement techniques can be applied effectively [3]. By integrating these theories, this study explores the various technological methods used to improve signal reception in 4G LTE networks and evaluates their effectiveness based on theoretical principles. The aim of this study is to do a comparative analysis on Improving Signal Reception in 4G Network. To achieve this goal, the specific research objectives were adopted.

1. To identify the common factors that affect signal reception quality in 4G LTE networks across different environments, including urban, suburban, and rural areas.
2. To evaluate the effectiveness of various signal enhancement techniques.
3. To compare the performance of selected signal improvement methods based on key parameters such as signal strength, data throughput, latency, and coverage.
4. To analyze the cost-effectiveness and scalability of each signal enhancement technique in real-world deployment scenarios.

2.METHODS

A comparative case study methodology was adopted to systematically analyse signal reception in 4G networks. Two scholarly research works were selected as representative case studies. These are:

Case Study A (Urban Environment)
Characterization of Radio Signal Strength and Quality in an Urban LTE Network focused on field drive tests in Lagos, Nigeria, to identify signal quality challenges in urban LTE environments [20].

Case Study B (Suburban/Rural Environment)
Performance Evaluation of Signal Boosting Techniques in Rural 4G LTE Deployments investigated signal booster deployment and MIMO configurations in Igbeti, Oyo State, Nigeria. [21].
These two studies were selected based on their detailed field methodology, use of standard LTE performance indicators, and application of signal improvement strategies.

Data Collection and Measurement Tools

These two case studies utilized similar field measurement tools, ensuring a basis for comparison as shown in table 1.

Table 1: Data Collection and Measurement Equipment/Tools

Equipment/Tool	Used in Case Study A	Used in Case Study B
TEMS Investigation Software	Yes	Yes
GPS-Enabled Test Devices	Yes	Yes
NetAct/NetMonster Apps	Yes	Yes
MATLAB for Analysis	Yes	Yes

ArcGIS/QGIS for Mapping	Yes	Yes

Both studies used standard 3GPP performance metrics namely, Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), Signal Interference plus Noise Ratio (SINR), Throughput, Latency, and Coverage Footprint. All these were captured in the comparative analysis.

Signal Quality Factors Investigated

The two studies identified various common and location-specific signal degradation factors. These are shown as tabulated in table 2.

Table 2: Investigated Signal Quality Factors

Signal Degradation Factor	Urban (Afolabi et al., 2018)	Rural (Adeyemi and Oseni, 2020)
High-Rise Building Obstruction	Major	Minimal
Cell Overshooting and Interference	Moderate	High (due to terrain)
Weak Backhaul Infrastructure	Low	High
Vegetation and Terrain-induced Fading	Minor	Major
User Congestion and handover failures	High	Low

Enhancement Techniques Evaluated

Each study implemented and also evaluated signal improvement strategies. The two approaches are shown in table 3. The goal of enhancement techniques is to optimize network performance to ensure the highest level of operational efficiency.

Table 3: Evaluated Enhancement Techniques

Enhancement Technique	Case Study A: Urban	Case Study B: Rural
Directional Antennas	Yes	Yes
Passive Repeaters	Yes	Yes
MIMO Antenna Configuration	Yes	Yes
Femtocells/Small Cells	Yes	No
eICIC Deployment	Yes	No
Signal Boosters	No	Yes

The effectiveness of these methods was assessed before and after deployment using empirical measurement and post-processing analysis.

Evaluation Metrics and Analysis Methods

Both studies used consistent Key Performance Indicators (KPIs) to analyse signal reception improvement. The KPIs and equipment used to measure and analyse them are shown in table 4.

Table 4: Evaluation Metrics and Methods of Analysis

Metric	Description	Tools/Equipment Used
RSRP	Signal Strength	TEMS, MATLAB
RSRQ	Signal Quality	TEMS, NetMonster
SINR	Signal-To-Interference Noise Ratio	TEMS, MATLAB
Throughput	Download/Upload Data Rates (Mbps)	Speed Test, Field Logs
Latency	Round-trip time delay (ms)	Ping Tools, Network Logs
Coverage	Area with signal ≥-100 dBm	ArcGIS, QGIS

Statistical methods such as mean comparison, standard deviation, and regression analysis were used to interpret the results. In the case study works, extensive computations were performed to get results as desired.

Comparative Performance Summary

The summary of the comparative performance evaluation exercise carried out in both case study research works is presented in table 5 with respect to the measured Key Performance Indicators (KPIs).

Table 5: Summary of the Comparative Performance Evaluation

Performance Metric	Improvement in Case A (Urban)	Improvement in Case B (Rural)
RSRP	+18% after MIMO/Small Cells	+25% after Boosters/Directional Antennas
SINR	+22% post eICIC deployment	+17% with signal booster
Throughput	32 Mbps to 50 Mbps	12 Mbps to 24 Mbps
Latency	Reduced from 68ms to 42ms	Reduced from 85ms to 58ms
Coverage	+15% geographic expansion	+20% geographic expansion

These results were summary of the evaluation got after computations in the case study works.

Scalability Analysis of the Enhancement Techniques

By scalability is meant the ability of the compared networks to variously handle increased network demand as the need arises. Scalability was analysed based on deployment of cost, complexity, and adaptability. To this effect, the results in table 6 were generated.

Table 6: Enhancement Techniques Scalability Analysis

Technique	Scalability (Urban)	Scalability (Rural)	Cost Rating	Ease of Deployment
Small Cells	Moderate	Low	High	Complex
Signal Boosters	Low	High	Low	Easy
Directional Antennas	Moderate	High	Medium	Moderate
MIMO Configurations	High	Moderate	Medium	Complex

3. RESULTS AND DISCUSSIONS

The key findings from the comparative evaluation of signal enhancement techniques in 4G LTE networks, based on the two case study research works are presented and discussed in this chapter. The analysis is structured around the five research objectives and evaluated using standardized KPIs namely, RSRP, RSRQ, SINR, Throughput, Latency, and Coverage Area.

Identification of Common Signal Degradation Factors

Both studies identified several environmental and technical factors affecting signal quality. These were summarized in table 2.

- **Urban (Case Study A)**

Dominant issues in this case study included multipath fading, building penetration losses, inter-cell interference, and handover failures due to high user density and physical obstructions such as skyscrapers.

- **Rural (Case Study B)**

Major challenges involved terrain-induced shadowing, low base station density, vegetation obstructions, and weak backhaul links.

Despite offering physical environments, both scenarios experienced degradation from signal attenuation and interference. However, urban environments suffered more from man-made factors such as building clutter, whereas rural areas were affected by natural obstructions and infrastructure limitations. These observations align with broader literature on LTE propagation in varying terrains.

Evaluation of Signal Enhancement Techniques

As shown in table 3, each case study deployed targeted signal enhancement methods.

- **Urban (Case Study A)**

In this case study, small cells, MIMO antennas, and eICIC techniques were effective in mitigating interference and improving signal capacity.

- **Rural (Case Study B)**

Directional antennas and low-cost signal boosters led to significant improvements in signal reach and quality. A summary of performance improvement is shown in table 7.

Table 7: Performance Improvement Summary

Metric	Case A (Urban)	Case B (Rural)
RSRP	-101 dBm to -85 dBm	-108 dBm to -88 dBm
SINR	+22% improvement	+17% improvement
Throughput	32 Mbps to 50 Mbps	12 Mbps to 24 Mbps
Latency	68 ms to 42 ms	85 ms to 58 ms
Coverage	+15% increase	+20% increase

Signal boosters and directional antennas offered cost-effective rural solutions, while MIMO and small cell deployments in urban areas improved capacity and interference management. The higher throughput gains in urban zones reflect the benefits of advanced LTE features like carrier aggregation and interference coordination, which are typically not feasible in sparse rural deployments due to interference costs.

COMPARATIVE PERFORMANCE ANALYSIS

Table 8 shows parameters obtained using average improvement rates across metrics in getting comparative performance analysis.

Table 8: Analysis of Comparative Performance

Technique	Urban Effectiveness	Rural Effectiveness
Small Cells	High (+60% capacity)	Low (due to backhaul)
Signal Boosters	Low	High (+30% coverage)
Directional Antennas	Medium	High
MIMO Antennas	High	Medium
eICIC	High (reduced ICI)	Not applicable

Urban deployments benefitted from spectrum re-use and densification, while rural areas relied on coverage-focused solutions. The effectiveness of each method was strongly linked to the environmental context and deployment cost feasibility.

Scalability of Signal Enhancement Techniques

The scalability was evaluated in terms of cost, technical complexity, and deployment feasibility. Table 9 shows the scalability presented in a tabular form derived from table 3.6.

Table 9: Signal Enhancement Techniques Scalability

Techniques	Cost	Scalability (Urban)	Scalability (Rural)
Small Cells	High	Moderate-High	Low
Signal Boosters	Low	Low	High
Directional Antennas	Medium	Moderate	High
MIMO Configurations	Medium	High	Moderate

Small cells and advanced MIMO systems, while effective, involve higher capital and maintenance costs, limiting their use in rural deployments. On the other hand, signal boosters and directional antennas offer simpler, scalable solutions for remote locations with minimal infrastructure.

4 CONCLUSIONS

This study concludes that signal reception quality in 4G LTE networks can be substantially improved by applying environment-specific enhancement techniques. Through a comparative analysis of two empirical research case studies, it is evident that the effectiveness and scalability of signal enhancement strategies are highly dependent on geographical, infrastructural, and economic factors. The research demonstrated that while urban environments benefit from capacity-boosting solutions, rural environments require coverage-focused, low-cost interventions. These insights are critical for mobile network operators, regulatory bodies, and infrastructure planners aiming to enhance 4G service quality and accessibility.

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