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Empirical Estimation of Received Signal Strength, Multipath Fading, and Delay Spread in a 5G Urban Deployment in Nigeria

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ABSTRACT
As 5G networks are being deployed globally, it is critical to understand their radio propagation characteristics, particularly in complicated metropolitan contexts, in order to guarantee optimal network design and optimization. This study presents an empirical assessment of key performance indicators such as Received Signal Strength (RSS), multipath fading, and delay spread in a 5G urban deployment in Abuja, Nigeria. Using realistic propagation models and measurement scenarios in densely built-up areas, the study evaluates how urban morphology influences signal degradation and variability. Results indicate that RSS deteriorates significantly with distance, with values decreasing from 53.90 dBm at 100 meters to 4.75 dBm at 1100 meters. Concurrently, path loss and multipath fading increase with distance, demonstrating the pronounced effect of reflections, shadowing, and scattering in urban environments. Delay spread and Doppler spread also show increasing trends, confirming heightened multipath effects and mobility-induced variability. The findings underscore the need for dense cell deployments and advanced signal processing techniques to maintain signal integrity and coverage in 5G networks across complex urban landscapes. This work provides critical insights for optimizing 5G deployments in Nigeria and similar urban environments across developing nations.

Keywords:
5G Networks,
Received Signal Strength (RSS),
Multipath fading,
Delay spread,
Urban Area.

INTRODUCTION

The evolution of mobile communication into the Fifth Generation (5G) marks a transformative leap in wireless technology, offering unprecedented data rates, ultra-low latency, massive connectivity, and enhanced capacity (Won and Choi, 2020; Le et al., 2016). As 5G networks are progressively rolled out globally, it is crucial to understand their radio propagation characteristics, especially in complex urban settings, to ensure effective network planning and optimization. In particular, estimating key parameters like Received Signal Strength (RSS), multipath fading, and delay spread is essential for gaining valuable insights into the performance and reliability of these networks (Mane, 2022; Alraih et al., 2022).

Received Signal Strength (RSS) is a key performance indicator (KPI) for wireless communication systems. It measures the power level of a received radio signal at the user equipment (UE) or mobile terminal, and it has a direct impact on coverage, handover choices, and overall link quality. In a 5G context with high data throughput and dependability, accurate RSS estimate is vital for network design and real-time performance evaluation (Anas et al., 2007; Karanja et al., 2023). RSS is commonly measured in decibels relative to one milliwatt (dBm), and it depends on various parameters, including the base stations broadcast power, antenna gains, the distance between the transmitter and receiver, and the propagation characteristics of the environment (Azoulay et al., 2023).

Multipath fading is a basic phenomenon in wireless communications caused by the transmission of radio signals over several propagation channels. Signals sent from a base station to a receiver in metropolitan areas are reflected, diffracted, and dispersed by a variety of obstacles, including buildings, automobiles, street furniture, and plants (Mahender et al., 2018). These many signal components, which travel different distances and arrive at different times and phases, combine at the receiver to cause constructive or destructive interference. This causes fast variations in the received signal's amplitude, phase, and occasionally frequency, a process known as fading (Puccinelli and Haenggi, 2006)

Multipath fading is more significant in 5G because it uses higher frequencies and bigger bandwidths, which are more subject to environmental interactions. Higher frequencies utilised in 5G, such as the sub-6 GHz range (e.g., 3.5 GHz) and millimeter-wave (mmWave) frequencies (24-40 GHz and beyond), exhibit more reflection and scattering, resulting in complicated multipath profiles. Unlike previous generations, which relied mostly on narrowband channels, 5G's wideband design makes it more vulnerable to temporal dispersion produced by multipath components (Rappaport et al., 2017).

In 5G New Radio (NR), signal strength is often assessed using the Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ) metrics, with RSRP serving as the 5G-specific counterpart of RSS. RSRP estimates the average received power of particular reference signals sent by the base station, allowing for a more consistent assessment of signal strength across vendors and configurations (3GPP, 2021). 5G networks operate on rarely used radio millimeter bands in the 30 GHz to 300 GHz range. Testing of 5G range in mmWave has produced results approximately 500 meters from the tower. Using small cells, the deployment of 5G with millimetre wave-based carriers can improve overall coverage area. Combined with beamforming, small cells can deliver extremely fast coverage with low latency. Low latency is one of 5G's most important features(Osseiran et al., 2016). 5G uses a scalable orthogonal frequency-division multiplexing (OFDM) framework. 5G benefits greatly from this and can have latency as low as one millisecond with realistic estimates to be around 1 – 10 seconds. 5G is estimated to be 60 to 120 times faster than the average 4G latency. Active antenna 5G encapsulated with 5G massive MIMO is used for providing better connections and enhanced user experience. Big 5G array antennas are deployed to gain additional beamforming information and knock out propagation challenges that are experienced at mmWave frequency ranges. Further, 5G networks clubbed with network slicing architecture enables telecom operators to offer on-demand tailored connectivity to their users that is adhered to Service Level Agreement (SLA) (Osseiran et al., 2016). Such customised network capabilities comprise latency, data speed, latency, reliability, quality, services, and security. With speeds of up to 10 Gbps as shown in Figure 1, 5G is set to be as much as 10 times faster than 4G (Osseiran et al., 2016)

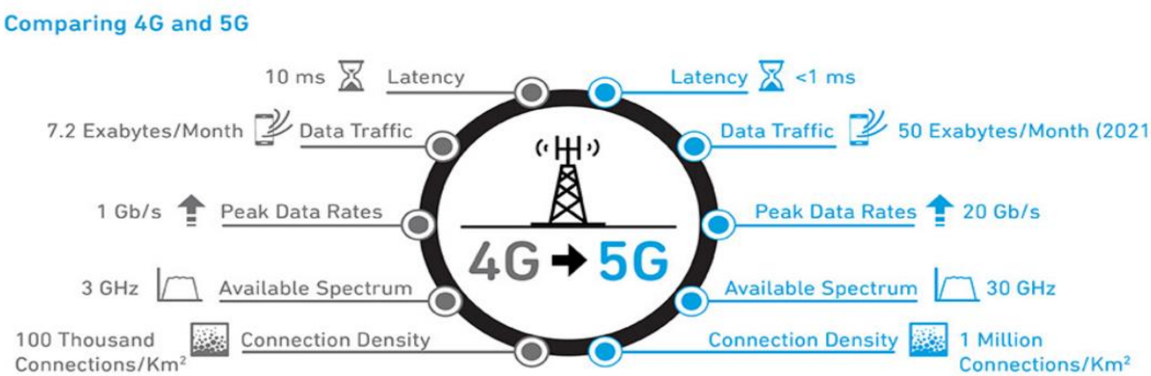


Figure 1: 4G vs 5G Network (Osseiran et al., 2016)

In urban environments, understanding the behaviour of 5G signals is crucial due to the complex propagation characteristics influenced by various factors such as buildings, vehicles, and other obstacles. This study focuses on estimating the Received Signal Strength (RSS), Multipath Fading, and Delay Spread in a 5G urban deployment in Nigeria. Urban area in Nigeria, most especially Abuja the Federal Capital Territory is characterized by high population densities, diverse architectural landscapes, and complex radio propagation conditions. These environments demand tailored solutions to meet the connectivity requirements of densely populated urban dwellers. Micro-cell deployment, which involves deploying small cells near users, emerges as a promising approach to address the capacity and coverage challenges in urban areas. Understanding the propagation characteristics and channel behavior in urban micro-cell environments is crucial for the successful deployment of 5G networks in Nigeria.

Path Loss and Its Impact on RSS

Path loss represents the attenuation of the signal as it propagates through space and interacts with physical obstacles. It is often modeled using empirical or semi-empirical models, such as the Log-distance Path Loss Model (Ezekwesili et al., 2025):

$$PL(d) = PL(d_0) + 10nlog_{10}\left(\frac{d}{d_0}\right) + X_\sigma \qquad (1)$$

where $PL(d_0)$ is the reference path loss at a known distance d_0, n is the path loss exponent (dependent on the environment, typically between 2 and 6), X_σ is a zeromean Gaussian random variable representing shadow fading (in dB)

The route loss exponent is larger in metropolitan contexts because of the presence of buildings, automobiles, and other barriers that produce reflection, diffraction, and scattering. This causes severe degradation in RSS with distance, particularly in non-line-of-sight (NLOS) conditions. Higher frequencies utilised in 5G (e.g., 3.5 GHz or mmWave) exhibit even greater attenuation, necessitating denser base station installations to maintain acceptable RSS levels.

Delay Spread

Delay spread quantifies the time dispersion of multipath signals and is critical for understanding intersymbol interference (ISI) in high-data-rate systems. The root mean square (RMS) delay spread is computed as:

$$\tau_{rms} = \sqrt{\frac{\sum_i P_i(\tau_i - \tau)^2}{\sum_i P_i}} \quad (2)$$

Where τ_i is the delay of the $i-th$ path, P_i is the received power of the $i-th$ path, τ is the mean excess delay

Accurate estimation of these parameters is especially pertinent in Nigeria's urban centers, where the radio environment can vary significantly due to unregulated infrastructure, varied urban morphology, and heterogeneous network deployments. Existing studies have primarily focused on developed regions (Zhimwang et al., 2023), and there is a need for context-specific analysis to guide efficient deployment in African urban areas. This paper presents a comprehensive empirical analysis of RSS, multipath fading, and delay spread in a real-world 5G urban deployment in Abuja, Nigeria.

MATERIALS AND METHODS

Modelling of 5G Network in Urban Environment with Tall Buildings

In urban settings, tall buildings create multipath propagation, where signals reflect off structures, causing interference and signal degradation. Measurements were taken in densely built areas to capture the impact of multipath fading, shadowing, and scattering.

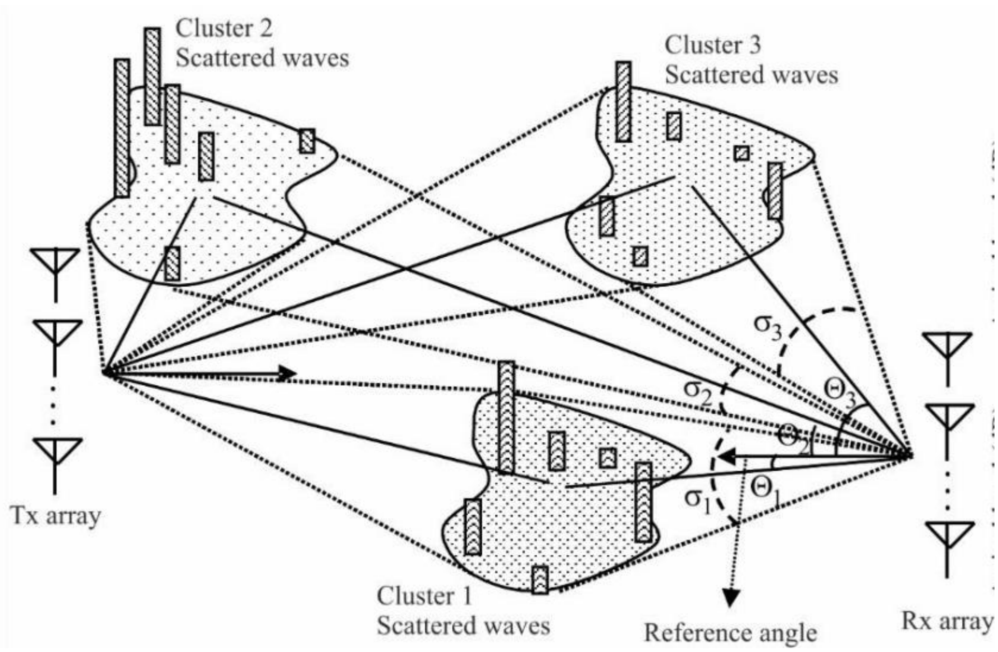


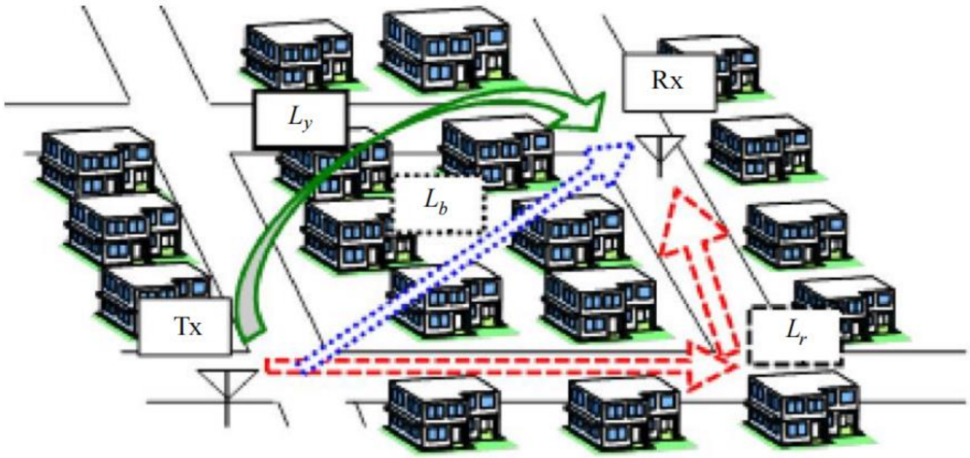
Figure 2: 5G Network in Urban Environment with Tall Buildings

The probability density function of the angular distribution of arrival waves within a cluster is expressed by:

$$P_i(\varphi - \Theta_i) = \frac{1}{\sqrt{2}\sigma_i} \cdot \exp\left(-\sqrt{2}\frac{|\varphi - \Theta_i|}{\sigma_i}\right) \quad (3)$$

where φ is the angle of arrival of arriving waves within a cluster in degrees referencing to the reference angle and σi is the standard deviation of the angular spread in degrees. Also, Θ_i = Cluster arrival angle, I, σ_i = standard deviation of angular spread within a cluster, i

Propagation model for paths between terminals located below roof-top height



$$L = -10\log(1/10^{(L_r/10)} + 1/10^{(L_b/10)} + 1/10^{(L_v/10)}) \tag{4}$$

$$L_r = \begin{cases} L_{rbc} & (before\ corner) \\ L_{rac} & (after\ corner) \end{cases} \tag{5}$$

$$L_{rbc} = 20\log(4\pi d/\lambda) \tag{6}$$

$$L_{rac} = L_{rbc} + \sum_i (7.18\log(\theta_i) + 0.97\log(f) + 6.1)\cdot\left\{1 - \exp\left(-3.72\cdot 10^{-5}\theta_i x_{1i} x_{2i}\right)\right\} \tag{7}$$

$$L_b = 20\log(4\pi d/\lambda) + 30.6\log(d/R) + 6.88\log(f) + 5.76 \tag{8}$$

$$L_v = 20\log(4\pi d/\lambda) + L_1 + L_2 + L_c \tag{9}$$

$$L_1 = 6.9 + 20\log\left(\sqrt{(v_1 - 0.1)^2 + 1} + v_1 - 0.1\right) \tag{10}$$

$$L_2 = 6.9 + 20\log\left(\sqrt{(v_2 - 0.1)^2 + 1} + v_2 - 0.1\right) \tag{11}$$

$$v_1 = (h_{bTx} - h_{Tx})\sqrt{\frac{2}{\lambda}\left(\frac{1}{a} + \frac{1}{b}\right)} \tag{12}$$

$$v_2 = (h_{bRx} - h_{Rx})\sqrt{\frac{2}{\lambda}\left(\frac{1}{b} + \frac{1}{c}\right)} \tag{13}$$

$$L_c = 10\log\left[\frac{(a+b)(b+c)}{b(a+b+c)}\right] \tag{14}$$

where, d: distance (m) between two terminals, λ: wavelength (m), f: frequency (GHz), θ_i: road angle of *i*-th corner (degree), x_{1i}: road distance from transmitter to *i*-th corner (m), x_{2i}: road distance from transmitter to *i*-th corner (m), R: mean visible distance (m), h_{bTx}: height of nearest building from transmitter in receiver direction (m), h_{bRx}: height of nearest building from receiver in transmitter direction (m), h_{Rx}: receiver antenna height (m), h_{Tx}: transmitter antenna height (m), a: distance between transmitter and nearest building from transmitter (m), b: distance between nearest buildings from transmitter and receiver (m), c: distance between receiver and nearest building from receiver (m)

RESULTS AND DISCUSSION

Table 1: Estimating RSS, Multipath Fading and Delay Spread for 5G Network

Distance (m)	Path Loss (dB)	RSS (dBm)	Multipath Fading (dB)	Delay Spread (ns)	Doppler Spread (Hz)	SNR (dB)
100	38.90	53.90	8.90	1044.57	872.35	31.23
200	46.91	61.13	8.57	898.50	835.29	32.30
300	79.78	40.95	9.28	1140.78	946.50	32.95
400	78.23	42.30	9.52	1059.55	960.58	33.78
500	88.79	34.75	9.52	1180.01	967.90	32.74
600	95.67	23.71	9.32	1159.05	1050.49	27.60
700	104.09	18.45	10.31	1314.64	1184.84	27.71
800	112.09	10.64	11.04	1305.57	1225.00	25.14
900	120.27	6.30	11.32	1335.45	1228.35	22.76
1000	123.06	6.10	11.35	1417.76	1276.90	18.59
1100	125.90	4.75	11.38	1458.49	1320.78	17.92

Table 1 estimate the RSS, multipath fading, delay spread among other parameters for 5G Network. Path loss increases significantly with distance, from 38.90 dB at 100 m to 125.90dB at 1100m. This increase in path loss is typical due to free-space attenuation and is exacerbated by multipath effects. The received power decreases with distance, from 53.90 dBm at 100 m to 4.75dBm at 1100m, which follows the expected trend. Higher path loss over distance results in lower received power at the receiver. Also, SNR decreases with distance, from 31.23 dB at 100 m to 17.92dB at 1100m. This indicates that as the signal travels farther; its strength diminishes relative to noise, leading to poorer signal quality. Delay spread and Doppler spread increase with distance, with values rising from 1044.57 ns and 872.35 Hz at 100 m to 1417.76 ns and 1276.90 Hz at 1000 m. This suggests more significant multipath propagation and mobility-induced Doppler effects as distance increases. Longer distances result in more multipath and Doppler effects

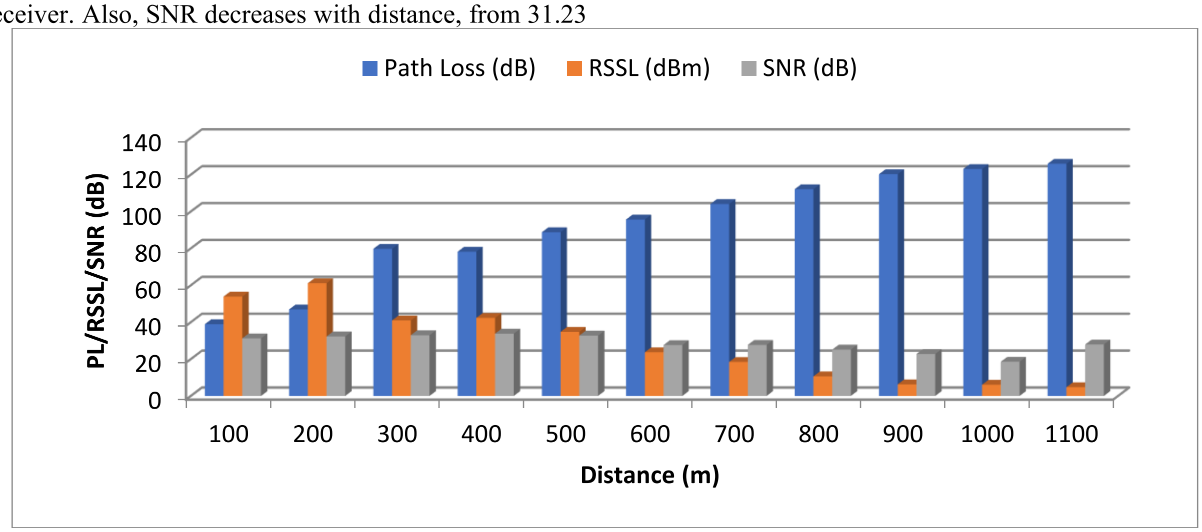


Figure 3: Comparing Path Loss, RSSL and SNR against distance

CONCLUSION

The empirical evaluation of 5G signal behaviour in an urban Nigerian context reveals significant insights into signal propagation challenges in dense environments. As distance from the transmitter increases, the study observed a sharp decline in RSS, with corresponding increases in path loss, delay spread, and Doppler spread. These variations are driven by urban obstacles such as buildings and vehicles, which induce multipath propagation, fading, and time dispersion. The findings confirm that the performance of 5G in urban environments is highly sensitive to distance and physical obstructions. Effective deployment strategies, such as small cell placement, beamforming, and massive MIMO, are essential to mitigate signal degradation. Additionally, the increasing delay and Doppler spreads suggest a need for robust equalization and channel estimation techniques to preserve signal quality.

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