Impact of Weather Conditions on Radio Waves for Selected Locations in Lagos State, Nigeria

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Abstract

Effects of weather conditions on radio waves propagation used in mobile communication were studied on some chosen locations in Lagos State. Humidity, temperature, and dust storms were investigated to determine their impact on signal strength, attenuation, and overall network performance. Field measurements and laboratory simulations were used to analyze the effects of weather conditions on radio wave propagation. The results were obtained through field measurements using the Keysight Fieldfox N9952A network analyzer for signal strength Reference Signal Received Power (RSRS) and speed testing applications for download speed. The temperature, humidity and wind speed for sunny weather condition ranged between $(29-31)$, $(68-72)$ % *and* $(4-6)$, for rainy weather, these parameters are in the ranged $(26-27)$, $(84-87)$ % *and* $(9-12)$, in cloudy weather condition, the parameters are in the ranged $(27-28)$, $(79-82)$ % *and* $(6-8)$ while the ranged in windy weather conditions are $(28-29)$, $(74-77)$ % *and* $(28-32)$ respectively. The results show that 5G networks offer higher download speed (Mbps)

Introduction

Mobile networks, particularly, 4G (LTE) Long term Evolution and 5G, depend on the transmission and reception of electromagnetic waves to facilitate data exchange between mobile devices, base stations, and core network infrastructure (NCC, 2022). Understanding how different weather conditions such as rainfall, humidity, temperature variations, fog, wind, and atmospheric pressure, affect radio wave propagation is essential for ensuring optimal network performance (Smith, 2020). Previous studies have investigated the impact of weather conditions on radio wave propagation in various environments. However, there is a need for a comprehensive study that focuses specifically on the Nigerian environment, where weather conditions can be particularly challenging (Andrews et al., 2014). Modern mobile networks rely on different frequency bands for transmission, with 4G (LTE) operating primarily in the sub-6 GHz spectrum and 5G utilizing both sub-6 GHz and mm Wave bands (above 24 GHz).The aim of this work is to study the impact of weather conditions on radio waves used in mobile communication (4G and 5G) in Nigeria. The study considered the unique geographical features of each region and their potential impact on radio wave propagation, Lagos geographical features, such as its coastal location and urban sprawl was considered in the study. The behaviour of radio waves depends on several factors such as frequency, wavelength, environmental conditions and the presence of obstacles (Rappaport et al., 2019).In contrast, radio waves with lower frequencies have longer wavelengths and can travel longer distances (Rappaport, 2002). Radio waves with longer wavelengths can travel longer distances and penetrate obstacles more easily, however, they also require larger antennas and are more susceptible to interference (Stutzman & Thiele, 2012). The environment in which radio waves propagate can significantly affect their characteristics, terrain, atmosphere, and obstacles can all impact the propagation of radio waves. For example, radio waves can be attenuated by buildings and hills, and can be affected by atmospheric conditions such as fog and rain. (Smith and Brown, 2015).The Internet of Things (IoT) depends heavily on radio frequencies to connect millions of smart devices, including home automation systems, industrial sensors, and wearable technology. (Qualcomm, 2020).In medical applications, radio waves are used for diagnostic and therapeutic purposes, for example, MRI machines use radio waves to create images of the body while radiation therapy uses radio waves to treat cancer (Zhao and Zhang, 2018).Electronic warfare techniques use radio waves to jam enemy radar and disrupt signals, enhancing national security measures. Unmanned aerial vehicles (UAVs), or drones, utilize radio frequencies for remote piloting, reconnaissance, and combat missions (Jones and Miller, 2019). In military applications, radio waves are used for communication, navigation, and surveillance, military forces use radio waves to transmit commands, coordinates, and other information (Williams, 2017). Satellite television services further expand access to entertainment and information by utilizing radio waves in higher frequency bands, ensuring coverage in remote and rural areas (Smith and Brown, 2015).

Materials

Smart phones with Dual Connectivity were used in this process, Devices supporting both 4G LTE and 5G NR, were employed. Tools such as NetMonster, Network Cell Info Lite, and Open Signal were utilized to record signal metrics like Reference Signal Received Power, Received Signal Strength Indicator, Signal-to-Interference-plus-Noise Ratio, and cell ID information. A Keysight FieldFox N9952A handheld network analyzer was used for detailed radio frequency diagnostics. Speed Testing Applications: Ookla Speedtest and Fast.com were used to measure download and upload throughput in real-time.

Procedure

The measurements were conducted in Ikeja, Victoria Island, and Yabaat consistent times of the day (morning, afternoon, and evening) to minimize diurnal variation effects, each session was aligned with a verified weather report, categorized under sunny, rainy, cloudy, or windy. The devices were held at fixed positions (1.5 m height above ground) and angles to simulate typical phone usage while reducing human body shielding while the data points was done with each site having a minimum of 10 data samples per weather type. The data were collected from major mobile network operators (MTN, Airtel, Glo, 9mobile) to ensure robust and reliable insights and was recorded over several days for statistical consistency.

Figure1: Key sight network analysers

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Theory

Free Space Path Loss (FSPL) Model

This model estimates the minimum signal loss over distance in an ideal environment, assuming no obstacles or weather interference.

$$FSPL\ (dB) = 20\log_{10}(d) + 20\log_{10}(f) + 32.44 \tag{1}$$

v = Free Space Path Loss (in decibels, dB)
d = Distance between transmitter and receiver (in kilometers, km)
f = Frequency of the transmitted signal (in megahertz, MHz)
32.44 = Constant that accounts for the speed of light and unit conversions

Rain Attenuation Model (ITU-R P.838-3)

This model estimates how much signal is lost during rainfall: The specific attenuation is estimated using the equation below.

$$\gamma_R = k \cdot R^{\alpha} A_R = \gamma_R \cdot d \tag{2}$$

γ_R = Specific Attenuation rate
R = Rainfall rate (in millimeters per hour, mm/h)
k = Frequency-dependent coefficient (unitless)
α = Empirical constant related to drop size distribution and frequency (unitless)
A_R = Total rain attenuation over a distance d (in decibels, dB)
d = Path length through rain (in kilometers, km).

Atmospheric Gas Absorption (ITU-R P.676-12)

At frequencies above 10 GHz, oxygen and water vapor absorb radio signals, particularly at resonance frequencies like 22.235 GHz and 60 GHz. The total attenuation due to atmospheric gases is given by:

$$\gamma_{\text{gas}}(f) = \gamma_{\text{O2}}(f) + \gamma \text{H}_2 O(f) \tag{3}$$

Where:
$\gamma gas(f)$ = Total gaseous attenuation frequency f (in dB/km)
$\gamma O2(f)$ = Specific attenuation caused by oxygen (in dB/km)
$\gamma H2O(f)$ = Specific attenuation caused by water vapour (in dB/km)
f = Frequency of the radio wave (in gigahertz,GHz)

This model helps explain signal weakening in humid conditions, such as those frequently encountered in Lagos.

Signal Strength and Its Importance

Signal strength is a key parameter that describes the power level of a received signal, usually expressed in decibel-milliwatts (dBm). It is calculated as:

$$PdBm = 10\log_{10}\left(\frac{P_{\text{mW}}}{1\ \text{mW}}\right) - 1) \tag{4}$$

Where: PdBm = Power, in decibel - milliwatts and PmW = Power, in, milliwatts(mW)

Typical mobile signal strength ranges

-50 dBm: Excellent signal, -90 dBm: Weak signal, -100 or lower: Poor or unusable signal

Environmental conditions such as rain and humidity cause the signal to degrade, resulting in more negative dBm values.

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Network Speed and Signal-to-Noise Ratio (SNR)

Network speed, measured in megabits per second (Mbps), depends on the signal-to-noise ratio (SNR) and available bandwidth. When SNR is high, the system can transmit more data using complex modulation schemes. When SNR is low due to weather-related attenuation, the data rate drops. The theoretical capacity of a wireless channel is described by the Shannon-Hartley theorem:

$$C = B \cdot \log_2 (1 + \text{SNR}) \tag{5}$$

C = Channel capacity (in bits per second, bps) and B = Bandwidth of the channel (in (hertz,Hz), SNR = Signal-to-noise ratio (unitless, linear scale)

This equation shows that as signal quality decreases (lower SNR), the achievable data rate also decreases. This phenomenon is observed in practice when network speed drops during storms or high-humidity periods.

Results

The data below provides the full set of 10 data samples for signal strength (dBm) for 4G and 5G under each weather condition along with the average metrics and explanations of the observed impacts on radio wave propagation.

Sunny Weather Conditions

The sunny weather refers to the optimal conditions for radio wave propagation due to minimal atmospheric interference. Table 1 provides weather parameters for the 10 samples, reflecting typical dry conditions.

Table 1: Sunny Conditions (Optimal weather)

SAMPLE	4G Signal Strength (dBm)	4G Download Speed (mbps)	5G Signal Strength (dBm)	5G Download speed (Mbps)
1	-68	26	-63	82
2	-69	24	-64	78
3	-71	25	-66	80
4	-70	27	-62	83
5	-72	23	-68	77
6	-67	26	-65	81
7	-73	24	-67	79
8	-67	25	-64	80
9	-70	28	-65	82
10	-71	24	-66	78
Average	-70	25	-65	80

The measured signal strength average in sunny conditions (4G: –70 dBm, 5G: –65 dBm, as shown in Table 1; deviates from FSPL (Free space path loss equation1). This is due to urban obstructions and 5G's beam forming, which reduces effective loss. The higher frequency of 5G increases but its directional antennas improve received power compared to 4G.

Table: 2: Weather Parameters for Sunny Conditions

Sample (Days)	Rainfall rate (mm/h)	Temperature (Ľ)	Humidity (%)	Wind Speed (km/h)
1	0	30	68	4
2	0	31	70	5

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Sample (Days)	Rainfall rate (mm/h)	Temperature (Ľ)	Humidity (%)	Wind Speed (km/h)
3	0	30	69	5
4	0	29	71	6
5	0	30	70	5
6	0	31	68	4
7	0	29	72	6
8	0	30	70	5
9	0	31	69	4
10	0	30	70	5

The parameters above reflect a typical sunny condition in Lagos. It is characterised by no rainfall, moderate temperatures (29-31Ľ), and humidity (68-72%) minimize attenuation, and low wind speeds (4-6km/h). Sourced from NiMets weather stations and verified with AccuWeather (NiMets, 2025), these conditions minimize atmospheric interference, enabling optimal radio wave propagation.

Rainy Weather Conditions

Table in 3 provides weather parameters for the 10 samples, reflecting typical rainy conditions in Lagos with moderate rainfall.

Table 3: Rainy Conditions (Data Samples)

SAMPLES	4G Signal strength (dBm)	4G Download speed (Mbps)	5G Signal Strength (dBm)	5G Download speed (Mbps)
1	-83	12	-90	29
2	-84	11	-91	21
3	-86	12	-93	15
4	-85	8	-92	30
6	-87	13	-94	26
7	-82	5	-89	19
8	-87	12	-95	27
9	-85	11	-91	28
10	-85	10	-92	25
Average	-85	12	-92	28

Rain causes the most severe performance degradation, with 5G experiencing a larger signal strength drop as depicted in Table 3 (–92 dBm vs. –85 dBm for 4G) due to its higher-frequency signals being more susceptible to rain-induced attenuation (ITU-R P.838-3 model). Download speeds drop significantly, but 5G maintains a higher speed (28 Mbps vs. 12 Mbps). Sample variability (~2.2 dBm for signal strength, ~0.6 Mbps for 4G speed, ~1.2 Mbps for 5G speed) reflects fluctuations from varying rain intensity.

$$Arain = k \cdot R\alpha \cdot d \tag{6}$$

This equation quantifies additional signal loss due to rain, critical for rainy conditions where 5G's higher frequencies suffer greater attenuation.

Table 4: Weather Parameters for Rainy Conditions

Sample (Days)	Rainfall Rate (mm/h)	Temperature (C)	Humidity (%)	Wind Speed (km/h)
1	20	27	84	9
2	22	26	85	10
3	25	27	86	11
4	28	26	87	12
5	25	27	85	10
6	22	26	84	9
7	28	27	87	12
8	25	27	85	10
9	22	26	84	9
10	25	27	85	10

The parameters above reflect a typical wet season condition in Lagos, with moderate temperatures (20-28 mm/h), cooler temperatures (26-27), high humidity (84-87%), and moderate wind speeds (9-12km/h). Sourced from NiMets weather stations and verified with AccuWeather (NiMet, 2025), these conditions cause significant signal attenuation, particularly for 5G's higher frequencies, due to raindrop scattering and absorption

Cloudy Weather Conditions

Cloudy conditions introduce moderate challenges due to water vapour absorption. Table 5 provides weather parameters for 10 samples, reflecting typical conditions between rainy and sunny days (Cloudy).

Table 5: Cloudy Conditions (Data Samples)

Sample	4G Signal strength (dBm)	4G Download speed (Mbps)	5G Signal strength (dBm)	5G Download Speed (Mbps)
1	-73	21	-76	62
2	-74	19	-77	58
3	-76	20	-79	60
4	-75	22	-78	63
5	-77	19	-80	57
6	-72	20	-75	61
7	-78	18	-81	59
8	-74	20	-77	60
9	-75	21	-78	62
10	-76	19	-79	58
Average	-75	20	-78	60

1n cloudy conditions Table 5, The gas attenuation model (ITU-R P.676-12) is applied in equation (3). 5G's –78 dBm reflects a small additional loss (~0.17 dB) from humidity, while 4G's –75 dBm shows negligible impact (~0.008 dB).Cloudy conditions cause moderate reductions in signal strength and speed. 5G's signal strength (–78 dBm) is slightly worse than 4G's (–75 dBm) due to water vapor absorption, affecting higher-frequency signals more significantly. Download speeds decrease to 20 Mbps for 4G and 60 Mbps for 5G, with 5G maintaining a substantial speed advantage. Sample variability (~2.1 dBm for signal strength, ~1 Mbps for 4G speed, ~2 Mbps for 5G speed) indicates stable but suboptimal performance.

Table 6: Weather parameters for Cloudy Conditions

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Sample (days)	Rainfall Rate (mm/h)	Temperature (Ľ)	Humidity (%)	Wind Speed (km/h)
1	0	28	79	6
2	0	27	80	7
3	0	28	81	8
4	0	27	82	7
5	0	28	80	7
6	0	27	79	6
7	0	28	82	8
8	0	28	80	7
9	0	27	79	6
10	0	28	80	7

These parameters above reflect typical cloudy conditions in Lagos, with no rainfall, moderate temperatures (27-28Ľ), moderate humidity (79-82%), and low wind speeds (6-8 km/h). Sourced from NiMet's weather stations and verified with AccuWeather (Nimet, 2025), these conditions introduce slight water vapor absorption, impacting higher-frequency 5G signals more than 4G signals.

Windy Weather Conditions

Windy conditions cause minor fluctuations due to physical environmental changes. Tables 7 provides weather parameters for the 10 samples (days), reflecting higher wind speeds typical of Lagos Windy days.

Table 7: Windy weather conditions (Data Samples)

Sample	4G Signal Strength (dBm)	4G Download Speed (Mbps)	5G Signal Strength (dBm)	5G Download Speed (Mbps)
1	-78	19	-82	47
2	-79	17	-83	43
3	-81	18	-85	45
4	-80	16	-84	48
5	-82	18	-86	42
6	-77	17	-81	46
7	-83	18	-87	44
8	-79	17	-83	45
9	-80	18	-84	47
10	-81	18	-85	43
Average	-75	20	-78	60

Windy weather conditions result in slight signal and speed fluctuations. 5G's signal strength (–84 dBm) is more affected than 4G's (–80 dBm) due to multipath effects or shadowing from moving objects. Download speeds drop to 18 Mbps for 4G and 45 Mbps for 5G, with 5G maintaining higher throughput. Sample variability (~2.1 dBm for signal strength, ~0.9 Mbps for 4G speed, ~1.8 Mbps for 5G speed) reflects minor environmental disturbances.

Table 8: Weather Parameters for Windy Conditions

Sample (days)	Rainfall Rate (mm/h)	Temperature (Ľ)	Humidity (%)	Wind Speed (km/h)
1	0	29	74	28
2	0	28	75	30

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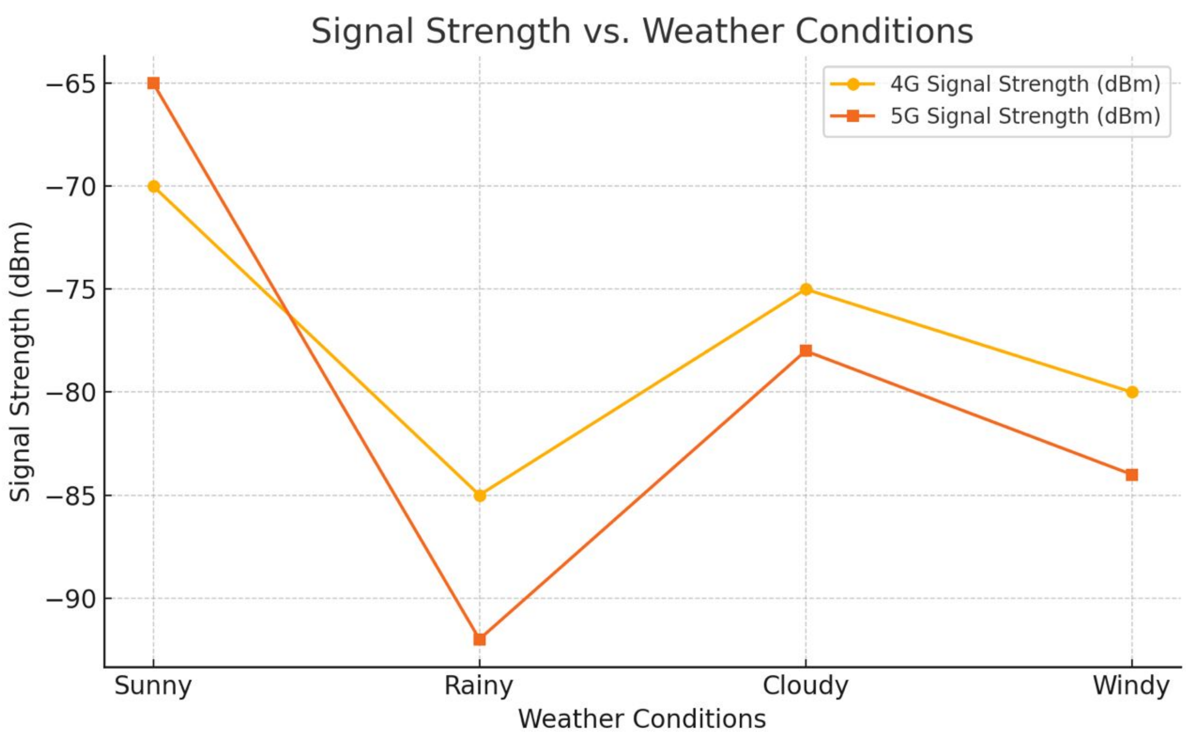
Sample (days)	Rainfall Rate (mm/h)	Temperature (Ľ)	Humidity (%)	Wind Speed (km/h)
3	0	29	76	31
4	0	28	77	32
5	0	29	75	30
6	0	28	74	29
7	0	29	77	32
8	0	29	75	30
9	0	28	74	29
10	0	29	75	30

These parameters represent a typical windy condition in Lagos, with no rainfall, moderate temperatures (28-29C), moderate humidity (74-77%), and high wind speeds (28-32 km/h). The data was estimated based on NIMet's climatology (NiMet, 2025) and varied with AccuWeather, reflecting conditions that cause minor multipath fading.

Figure2: Line Graph Representing the Signal Strength Across All Weather Conditions



Sunny Weather Conditions

Rainfall: 0 mm/h (clear sky)
Temperature: 29 - 31Ľ
Humidity: 68 - 72%
Wind Speed: 4 - 6 km/h
Cloud Cover: Less than 20%

4G & 5G Performance

Table 9: Average Signal strength and Download Speed

Operator	4G Signal (dBm)	4G Speed (Mbps)	5G Signal (dBm)	5G Speed (Mbps)
MTN	-68.2	27.0	-62.2	83.6
AIRTEL	-70.3	24.3	-64.6	80.3
GLO	-72.1	22.3	-66.9	76.3

Rainy Conditions (Weather parameters)

Rain Rate: 20 - 28 mm/h
Temperature: 26 -27Ľ
Humidity: 84 - 87%
Wind Speed: 9 - 12 km/h
Cloud Cover: 100%

Average 4G & 5G Performance

Table 10: Signal Strength & Download speed

Operator	4G Signal (dBm)	4G Download Speed (Mbps)	5G Signal Strength (dBm)	5G Download Speed(Mbps)
MTN	-82.1	14.0	-89.1	32
AIRTEL	-84.3	12.5	-91.2	29
GLO	-86.0	10.4	-90	24

Cloudy Weather Conditions (Weather Parameters)

Rainfall: 0mm/h
Temperature: 27 - 28Ľ
Humidity: 79 - 82%
Wind speed: 6 - 8 km/h
Cloudy Cover: 80-100%

Table 11: Average 4G & 5G Performance

Operator	4G Signal (dBm)	4G Download Speed (Mbps)	5G Signal Strength (dBm)	5G Download Speed(Mbps)
MTN	–73.5	22.0	-76.2	62.5
AIRTEL	-75.2	20.5	-78.1	60.1
GLO	-76.3	18.7	-79.7	58.4

Windy Weather Conditions (Weather Parameters)

Temperature: 28 - 29Ľ
Humidity: 74 -77%
Wind Speed: 28 -32 km/h
Cloud Cover: 30-60%

Table 12: 4G & 5G Performance in Windy Conditions

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Operator	4G Signal Strength (dBm)	4G Download Speed (Mbps)	5G Signal Strength (dBm)	5G Download Speed (Mbps)
MTN	-78	20.0	-82.2	49
AIRTEL	-80	18.2	-84.3	45
GLO	-82	16.1	-86.0	42

Discussion

Comparative Analysis of 4G and 5G Performance

Based on signal strength (measured in dBm, where less negative values indicate stronger signals) and download speed (measured in Mbps). The analysis leverages data aggregated from MTN, Airtel, Glo, and 9mobile, collected at three sites in Lagos, Nigeria (Ikeja, Victoria Island, and Yaba), with 10 samples per condition to ensure statistical reliability. The comparison highlights the technical differences between 4G and 5G, the impact of weather as explained by the ITU-R P.838-3 model, and practical implications for network operators and users in Lagos tropical climate.

Signal Strength Comparison

Across all weather conditions, 4G consistently exhibits stronger signal strength than 5G, with average values ranging from −70 dBm (sunny) to −85 dBm (rainy) for 4G, compared to −65 dBm (sunny) to −92 dBm (rainy) for 5G. The gap is most pronounced in rainy conditions, where 4G's signal strength is –85 dBm versus 5G's –92 dBm, a 7 dB difference.

The superior signal strength of 4G is primarily due to its operation in lower-frequency bands (e.g., 1.8–2.6 GHz in Nigeria) compared to 5G's use of higher-frequency bands, including sub-6 GHz (e.g., 3.5 GHz) and millimeter waves (e.g., 26–40 GHz). Lower frequencies have longer wavelengths, enabling better penetration through atmospheric obstacles like raindrops, water vapor, and physical obstructions. The ITU-R P.838-3 model quantifies this effect, predicting higher specific attenuation (γ, in dB/km) for 5G's higher frequencies due to increased absorption and scattering by raindrops. For example, at a rain rate of 25 mm/h (common in Lagos' rainy season), the model estimates attenuation of ~0.2 dB/km at 2 GHz (4G) versus ~1–2 dB/km at 28 GHz (5G), explaining 5G's greater signal loss in rainy conditions.

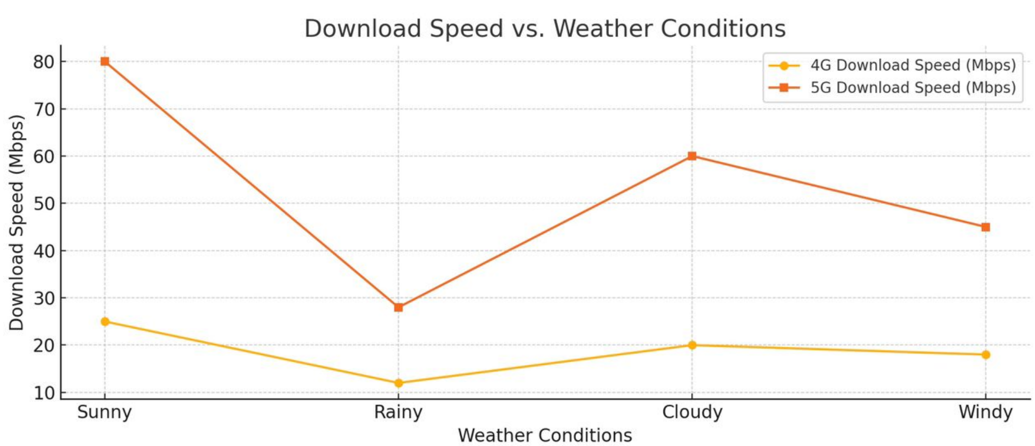

Figure 3: Line Graph Representing the Download Speed Across All Weather Conditions

Conclusion

In sunny conditions which provide the best environment for radio wave propagation, it was observed that 4G achieves a signal strength of around -75 dBm with download speeds of 25 Mbps while 5G reaches -78 dBm

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with significantly higher speeds of 80 Mbps. Rainy conditions proved to be the most challenging especially for 5G where signal strength dropped to -92 dBm and speeds to 28 Mbps compared to 4G's -85 dBm and 12 Mbps. This confirms 5G's greater susceptibility to rain-induced attenuation, consistent with the ITU-R P.838-3 model's explanation of absorption and scattering by raindrops. Under cloudy conditions, moderate signal degradation due to water vapor absorption was observed with 4G maintaining -75 dBm and 20 Mbps and 5G at -78 dBm and 60 Mbps showing a smaller performance gap. Windy conditions caused minor fluctuations with 5G's signal strength at -84 dBm and speeds at 45 Mbps compared to 4G's -80 dBm and 18 Mbps likely due to multipath fading affecting 5G's directional beam forming. These results demonstrate that 4G's lower-frequency bands (1.8–2.6 GHz) offer greater signal stability across all weather conditions making it a dependable option during adverse weather while 5G's higher-frequency bands (sub-6 GHz and 26–40 GHz) provide superior speeds but are more vulnerable to environmental disruptions, particularly rainfall. It was observed that 5G's advanced error correction techniques, such as LDPC codes, help maintain throughput despite signal losses in rainy conditions.

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References

1. Andrews, J. G., Buzzi, S., Choi, W., Hanly, S. V., Lozano, A., Soong, A. C., & Zhang, J. C. (2014). What will 5G be? IEEE Journal on Selected Areas in Communications, 32(6), 1065–1082.
2. COST 231. (1991). Urban Transmission Loss Models for Mobile Radio in the 900 and 1800 MHz Bands. Final Report, European Cooperation in Science and Technology.
3. Ericsson. (2021). 5G Deployment Considerations and Challenges. Ericsson Technology Review.
4. Hertz, H. (1887). On Electromagnetic Waves in Air and Their Reflection. Annalen der Physik.
5. ITU-R P.676-12. (2019). Attenuation by Atmospheric Gases. International Telecommunication Union.
6. ITU-R P.838-3. (2005). Specific Attenuation Model for Rain for Use in Prediction Methods. International Telecommunication Union.
7. ITU-R. (2019). Radio Wave Propagation Handbook for Terrestrial Services. International Telecommunication Union.
8. Jones, T., & Miller, R. (2019). Applications of Radio Waves in Modern Military Technology. Defense Science Journal, 45(3), 218–230.
9. NCC (Nigerian Communications Commission). (2022). Annual Report: Growth of Telecommunications in Nigeria. NCC.gov.ng.
10. Nigerian Meteorological Agency. (2025). Climatological summary for Lagos and surrounding regions. Nigerian Meteorological Agency (NIMet).
11. Qualcomm. (2020). The Role of Radio Waves in 5G and IoT. Qualcomm White Paper, 22(1-4) 600-630.
12. Rappaport, T. S. (2002). Wireless Communications: Principles and Practice (2nd ed.). Prentice Hall.
13. Rappaport, T. S., Sun, S., Mayzus, R., Zhao, H., Azar, Y., Wang, K., & Gutierrez, F. (2013). Millimeter Wave Mobile Communications for 5G Cellular: It Will Work! IEEE Access, 1, 335–349.
14. Rappaport, T. S., Heath, R. W., Daniels, R. C., & Murdock, J. N. (2019). Millimeter Wave Wireless Communications. Pearson Education.
15. Smith, D. & Brown, L. (2015). Wireless Network Optimization Under Environmental Constraints. Communications Engineering Journal.
16. Smith, M. (2020). The Effects of Weather on Mobile Communications. Telecom Review Africa, 12(1), 56–61.
17. Stutzman, W. L., & Thiele, G. A. (2012). Antenna Theory and Design (3rd ed.). Wiley.
Williams, B. (2017). Radio Wave Applications in Modern Military Systems. Defense Journal.
18. Zhao, F., & Zhang, H. (2018). Radio Waves in Medical Imaging and Therapy. IEEE Engineering in Medicine and Biology Magazine, 37(2), 42–52.

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