Impact of Altitude and Weather Conditions on Cellular Networks: A Comprehensive Analysis of Quality of Service

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ABSTRACT

This study investigates the influence of altitude and weather conditions on the performance of cellular networks through a detailed analysis of empirical data. The study examines multiple parameters including threshold levels, fade margins, download speeds, packet loss percentages, and mobile Signal Quality Index (SQI) under varying altitudes and weather scenarios. Altitude variations are explored in relation to signal propagation and quality, revealing nuanced effects on fade margins and signal strength. Weather conditions, particularly rainy weather, are shown to significantly impact quality of service, leading to decreased download speeds, higher packet loss rates, and reduced mobile SQI. The findings highlight the importance of fade margins in ensuring reliable communication, with higher values indicating greater resilience to signal degradation. Despite variations in altitude and weather, mobile SQI remains relatively stable, suggesting that the network maintains acceptable service quality levels for users. This research contributes to a deeper understanding of the complex interplay between environmental factors and cellular network performance, providing valuable insights for network operators and engineers in optimizing network design and maintenance strategies. Further research in this area could focus on developing predictive models to anticipate network performance based on altitude and weather forecasts, ultimately enhancing user experience and service reliability in diverse geographic regions.

Keywords - **Altitude, Weather conditions, Cellular network, Quality of Service, Download speeds, Packet loss, Mobile Signal Quality Index (SQI), Rain attenuation and Network optimization**

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I. INTRODUCTION

The term cellular network refers to a wireless mobile network that divides its coverage area into sectors and cells, allowing for the reuse of frequencies and the use of low-power transmitters over land regions known as cells. Each cell site is powered by at least one fixed-location transceiver [1]. Instead of using wires or cables like copper or optical fibre for transmission, a wireless mobile network uses electromagnetic waves within a certain frequency range to send data and speech across great distances. The kind of radio communication system that is employed is determined by user requirements, radio spectrum allocation, regulations, standards, and technology [2]. The generation of mobile technology includes, the global system for mobile (GSM), code division multiple access (CDMA), universal mobile telecommunication services (UMTS) and long term evolution (LTE). As far as telecommunication services are concerned, Quality of Service (QoS) requirements are highly demanding and their compliance is critical owing to the type of users of these services

Quality of Service (QoS) in cellular networks is defined as the capability of the cellular service providers to provide a satisfactory service which includes voice quality, signal strength, low call blocking and dropping probability, high data rates for multimedia and data applications among others. It allows network engineers to prioritise particular high-performance applications, hence adjusting total network traffic. To ensure the good performance of vital applications that need a lot of bandwidth for real-time traffic, quality of service (QoS) is crucial. Users expect good performance at all times, and the newest online apps and services need enormous amounts of bandwidth and network speed. Thus, it is necessary to use techniques and devices that ensure the highest quality of service [3]. Additionally, as the Internet of Things (IoT) develops further and machines use networks to deliver real-time status reports on any possible problems, QoS becomes more and more significant. Consequently, any feedback lag might result in extremely expensive errors when it comes to IoT networking. Quality of Service guarantees that data travels as fast as feasible throughout the network and allows the data stream to take precedence [4].

The major challenges when considering QoS in cellular networks are varying rate channel characteristics, bandwidth allocation, fault tolerance levels and handoff support among heterogeneous wireless networks. In 1G and 2G networks such as GSM and CDMA there was only one aspect of QoS and it is voice. Providing quality speech was the major concern. Now in 3G and 4G networks, QoS has to be provided for voice as well as data. Still priority is given for voice services as they are considered as the primary service [5]. They are very delay sensitive and require real - time service. Data services are comprised of text and multimedia. These services are less delay sensitive but expect better throughput and less or no loss rate. Throughput is the amount of data which a network or entity sends or receives data, or the amount of data processed in one determined time space. It has as basic units of measures the bits per second (bit/s or bps). The throughput can be lower than the input tax due to losses and delays in the system. Throughput is a good measure of the channel capacity of a communications link. Due to their high frequencies, a greater proportion of base stations are linked via microwave connections, which enable them to transmit vast amounts of data [6] [7].

The microwave signal is released from the transmission wire by the antenna's transmitting end and travels across empty space at the speed of light. Rain, relative humidity, and temperature are just a few of the atmospheric factors that impact the signal as it moves from the transmitter to the receiver. However, rain, among other atmospheric phenomena, is the major source of terrestrial microwave signal degradation that resulted to poor QoS [8] [9]. Rain droplets absorb, scatter and depolarize the energy of radio waves thereby reducing the amount of RF energy reaching the receive antenna. During rainfalls, scattering and absorption of the signals by the raindrops causes propagation impairment, such as signal attenuation. Therefore, attenuation due to rainfall becomes one of the most important limitations to the good QoS [10]. The attenuation effects become very severe, particularly in the tropics with heavy rainfalls.

The effect of rain attenuation on terrestrial microwave links have led to the development of rain rate and rain attenuation models. These models are used to predict the point rainfall-rate cumulative distribution of any location and several of such models exist. However, some of them have one discrepancy or the other, such as the number of stations and data available and not all the stations satisfy the one-minute integration time requirement [11] [12].

Modeling the attenuation of RF signals by atmospheric gases is a well- established process that is outlined in ITU recommendation. The recommended approach is to use local atmospheric measurements along with the ITU models to predict the expected amount of absorption. For the frequencies in the range of 2-40 GHz, oxygen and water vapor are the dominant attenuation factors in the atmosphere. For terrestrial links where both terminals are at or near the same altitude, the atmosphere can be treated as constant over the path. In this case it makes sense to characterize the absorption as a specific attenuation value in dB/km, which can be applied to the path distance to determine the total attenuation [13] [14] [15]. The expression for the total loss due to atmospheric absorption on a terrestrial path is

$$A = \gamma_0 d \text{ dB} \qquad (1)$$

Where d is the line-of-sight distance between the terminals in km and γ_0 is the specific attenuation of the atmosphere in dB/km. The specific attenuation of the atmosphere is given by the sum of the specific attenuation due to water vapor and that due to oxygen (Igbekele et al., 2020):

$$\gamma_a = \gamma_0 + \gamma_n \qquad (2)$$

Where γ_0 is specific attenuation due to water and γ_n is specific attenuation due to oxygen

Receiver Sensitivity

Receiver Sensitivity is the minimum signal-to-noise ratio times the mean noise power as shown in equation (3). Sensitivity in a receiver is usually taken as the minimum input signal (Smin) required to produce a specified output signal having a specified signal-to-noise (S/N) ratio. System level sensitivity is the minimum required operational sensitivity and is given as in equation (4).

Receiver Sensitivity (Minimum Signal),

$$S_{min} = (S/N)_{min} k T_0 B(NF) \qquad (3)$$

Minimum Operational Sensitivity,

$$MOS = (S/N)_{min} k T_0 B(NF)/G \qquad (4)$$

where S/Nmin is the Minimum signal-to-noise ratio needed to process a signal, NF is the noise figure/factor, k the Boltzmann's Constant is 1.38 x 10^{-23}Joule/^{0}K, T_o is the absolute temperature of the receiver input and is 290^{0}K, B is the receiver bandwidth (Hz) and G is the antenna/system gain [4].

Free Space Loss and Effective Isotropic Power

As an electromagnetic wave propagates in free space, the power density per unit area decreases in proportion to the frequency and the square of the distance from the source. This formulates the standard free space loss in equation 5.

Free Space Loss (any frequency) using decibels to express the loss and using a generic frequency f, is given by [7]:

$$FSL = 92.45 + 20^{*}log(D) + 20^{*}log(f) \qquad (5)$$

where FSL is expressed in dB, D is in km and f is in MHz. Also, the effective isotropic radiated power EIRP is given by

$$\text{EIRP} = T_x - L_{coax\,tx} + L_{coax\,tx} \qquad (6)$$

Received Signal Level

This is the actual power delivered to the receiver in excess of that required for a minimum level of performance so as to guarantee a reliable link. Received signal level RSL is given by

RSL = EIRP - FSL + RX Antenna Gain – Coax Cable Loss

$$\text{RSL} = T_x - L_{coax\,tx} + G_{tx} - \text{FSL} + G_{rx} - L_{coax\,rx}$$
(7)

where T_x is the transmit power in dBm, G_{tx} is the transmit antenna gain in dBi, G_{rx} is the receive antenna gain in dBi and L_{coax} is the cable loss at transmit and receive in dB.

II. MATERIALS AND METHOD

Experimental Site

The research was carried out in the city of Jos, Plateau State. Plateau is under the effect of both tropical and temperate climate [16], otherwise described as semi-temperate climate zone. However, significant differences in climatic conditions and therefore in precipitation characteristics are observable between diverse areas of the state as a result of the irregular topography, compared with most parts of Nigeria. Plateau region is affected by climatic and geographical factors like latitude, distance from sea, distribution of air pressure systems and global winds as well as mountain barriers. These factors affect the rain attenuation parameters such as rain shape, drop-size, distribution, temperature and rain rate [16] [17]. The study of climatic zones in Plateau-Nigeria is very vital for the design of link budget because of the peculiarities of Plateau; its semi-temperate climate, the guinea savanna zone and its topography characterized with tall mountains and high surface pressure. The study location was grouped in five clusters (PLA010, PLA011, PLA012, PLA024, and PLA048) and each cluster has a different Altitude.

Data Collection

Davis weather station was used to measure rainfall rate (mm/h) data for the year 2021. The rain rate was estimated and analyzed based on the measured data and the corresponding rain attenuation over the microwave backhaul link. The procedure of ITU model (ITU-R P.530-18, 2021) for terrestrial microwave rain attenuation prediction was used to obtain percentage of time of exceedance at varied rain rates and to determine Plateau clusters rainfall rate exceeded at the critical availability level of 0.01% of the average year. This was used to determine the propagation losses due to rain.

Cumulative distribution of rainfall intensity was obtained to find the probability of exceedance of each of the rainfall rate value in the data. The value with low probability of exceedance was determined from the graph of rainfall rate against exceedance probability to determine its corresponding rain attenuation value. Tools/Equipment used to conduct this study are 3G/4G cell sites backhaul links, microwave parabolic reflector antennas, huawei RTN605/620/910, alcatel Melody Lux 40, outdoor transceiver units, indoor radio units, personal computer (PC) and connecting cable/connectors (coaxial and fibre cables). Huawei RTN and Alcatel Melody Lux radio units were connected to the assemblage of outdoor RF units for measuring the received signal levels. Radio links backhauling 3G and 4G cell sites traffic to the BSC and RNC respectively were established and investigated during normal and rainy conditions. The link operating frequencies for both the transmitter and receiver and other radio parameters were configured based on ITU-R P530-8/9 link budget document. The rain rate measurements using Davis weather station were concurrently carried out and accurately logged. Microsoft Excel Trend-line function plots and packages were used to process and analyse the annual rain rate and rain attenuation.

III. RESULT AND DISCUSSIONS

Table 1 shows the received signal level (RSL) under different conditions. The no rain condition serves as a baseline reference for signal strength under normal weather conditions. There is a clear trend of decreasing RSL with increasing rain rate. As the rain rate goes up from 80.00 mm/h to 130.00 mm/h, the RSL during rain decreases gradually from -51.76 dBm to -56.52 dBm. This indicates that higher rainfall intensity leads to greater signal attenuation and weaker signal reception. The result highlights the significant impact of rain on signal strength in mobile cellular network. As rain intensity increases, more raindrops in the signal path cause greater attenuation, resulting in weaker received signals. This degradation in signal strength during rain can lead to reduced network performance, slower data transfer rates, and potentially dropped connections. There is a clear positive correlation between rain rate and rain attenuation. As the rain rate increases from 80.00 mm/h to 130.00 mm/h, the rain attenuation also increases gradually from 9.81 dB to 14.57 dB. This indicates that higher rain rates lead to greater signal attenuation, resulting in a more substantial reduction in signal strength.

Table 1: Received signal level (RSL)

Rain Rate (mm/h)	Transmit Power (dBm)	RSL without rain (dBm)	RSL during rain (dBm)	Rain Attenuation (dB)
80.00	20.00	-41.95	-51.76	9.81
82.00	20.00	-41.95	-52.44	10.49
84.00	20.00	-41.95	-53.05	11.10
86.00	20.00	-41.95	-53.51	11.56
88.00	20.00	-41.95	-53.93	11.98
90.00	20.00	-41.95	-54.63	12.68
92.00	20.00	-41.95	-55.31	13.36
100.00	20.00	-41.95	-55.47	13.52
120.00	20.00	-41.95	-56.04	14.09
130.00	20.00	-41.95	-56.52	14.57

Table 2 presents the results for the data service under clear sky and rainy conditions. Under clear sky circumstances, there appears to be a small variation in download speeds with altitude. Thus, average download speeds are 3.46 Mbps and 3.30 Mbps at lower altitudes (1123.19m and 1161.59m), respectively, and 3.00 Mbps and 4.12 Mbps at higher altitudes (1180.49m and 1192.38m). In the same way, download speeds fluctuate with height under rainy conditions. Thus, during rainy conditions, the download rates at lower elevations (1123.19m and 1161.59m) are 2.11 Mbps and 2.36 Mbps, respectively. Conversely, the rates decrease to 1.13 Mbps and 4.10 Mbps, respectively, at greater altitudes of 1192.38m and 11180.49m. The study suggests that there is no consistent trend regarding the effect of altitude on network performance. While some sites at higher altitudes exhibit lower download speeds, others show higher speeds. This inconsistency could be attributed to various factors, such as terrain characteristics, distance from cellular towers, and weather conditions.

Table 2: Data Service under clear sky and rainy conditions

Study Site Code	**Study Centre Altitude (m)**	**Threshold Level (dBm)**	**Fade Margin (dB)**	**Download Speed at Clear Sky (Mbps)**	**Download Speed during Rain (Mbps)**	**Packet Loss (%)**	**RSL (dBm)**
PLA024	1123.19	-82.00	51.05	3.46	2.11	39.60	-30.95
PLA011	1161.59	-82.00	49.80	3.30	2.36	28.80	-32.20
PLA012	1170.74	-68.50	41.22	4.29	4.26	0.70	-27.00
PLA010	1180.49	-74.50	32.54	3.00	1.13	62.30	-41.95
PLA048	1192.38	-68.50	37.21	4.12	4.10	0.40	-31.29

Table 3: Voice Service under clear sky and rainy conditions

Study Center Code	**Study Centre Altitude (m)**	**Threshold Level (dBm)**	**Fade Margin (dB)**	**Mobile SQI at Clear Sky**	**Mobile SQI during Rain**	**RSL (dBm)**
PLA024	1123.19	-82.00	51.05	+23.00	+19.00	-48.20
PLA011	1161.59	-82.00	49.80	+23.00	+19.00	-49.70
PLA012	1170.74	-68.50	41.22	+25.00	+20.00	-44.20
PLA010	1180.49	-74.50	32.55	+22.00	+20.00	-52.10
PLA048	1192.38	-68.50	37.21	+25.00	+20.00	-52.90

Table 3 presents voice service by evaluating the Mobile Signal Quality Index (SQI) under clear sky and rainy conditions. SQI is a metric used to assess the quality of the received signal. A higher SQI indicates better signal quality. There's a slight decrease in SQI during rain compared to clear sky conditions across all altitudes. This indicates that rain has a minor detrimental effect on the quality of the received signal, as expected due to increased attenuation and interference caused by precipitation

IV. CONCLUSION

This study offers valuable insights into the performance of cellular networks under varying conditions, such as altitude and weather. Rainy weather conditions adversely affect signal quality, leading to decreased download speeds, higher packet loss percentages, and a reduced mobile Signal Quality Index (SQI). Rain attenuation results in decreased signal strength and increased fade margins, highlighting the need for robust network infrastructure and signal processing techniques to maintain satisfactory service quality during adverse weather conditions. SQI serves as a key indicator of signal quality perceived by mobile devices. Despite variations in altitude and weather conditions, SQI remains relatively stable, suggesting that the network maintains acceptable service quality levels for users under varying environmental conditions. The study highlights the importance of considering factors such as altitude and weather conditions in the design, optimisation, and maintenance of cellular networks. By understanding the impact of these factors on signal propagation and quality, network operators can implement strategies to enhance service reliability, minimise disruptions, and ensure an optimal user experience across diverse geographic regions and weather conditions. Engineers and network planners can use this study to design systems with adequate margins to compensate for rain-induced signal attenuation and ensure reliable communication under varying weather conditions.

REFERENCES

[1]. Harrison, K., Mishra, S. M., & Sahai, A. (2010). How much white-space capacity is there? In new frontiers in dynamic spectrum. *IEEE Symposium. 5*, 1–10.

[2]. Wayne, T. (2007). *Electronics communication system: Fundamental through advanced.* New Delhi: Dorling Kindersley.

[3]. Zhimwang J. T., E., P. Ogherohwo, Agbalagba O. E., Yemi S. O., Shaka O. S., Ibrahim A., and Mamedu C. E. (2023). Nigeria Digital Terrestrial Television Broadcasting: An Evaluation of the Transmitted Signal received under different environmental features in North-Central Region. *Int. J. Advanced Networking and Applications*, 14(6), 5722 – 5726. https://doi.org/10.35444/IJANA.2023.14609

[4]. Odesanya Ituabhor, Isabona Joseph, Jangfa Timothy Zhimwang, Ikechi Risi (2022). Cascade Forward Neural Networks-based Adaptive Model for Real-time Adaptive Learning of Stochastic

Signal Power Datasets. International Journal of Computer Network and Information Security.3. 63-74. https://doi.org/10.5815/ijcnis.2022.03.05

[5]. Yahaya Yunisa, Jangfa Timothy Zhimwang, Ogherohwo Enoh Pius, Ibrahim Aminu, Shaka Oghenemega Samuel, Frank Lagbegha-ebi Mercy (2022). Evaluation of Signal Strength and Quality of a Ku-Band Satellite Downlink during Raining Season in Guinea Savanna Region of Nigeria. *Int. J. Advanced Networking and Applications*. 13(5). 5037-5044. https://doi.org/10.35444/IJANA.2022.13502

[6]. Isabona Joseph, Odesanya Ituabhor, Jangfa Timothy Zhimwang, and Risi Ikechi (2022). Achievable Throughput over Mobile Broadband Network Protocol Layers: Practical Measurements and Performance Analysis. *Int. J. Advanced Networking and Applications*. 13(4). 5037-5044. https://doi.org/10.35444/IJANA.2022.13404

[7]. J. T. Zhimwang, E. P. Ogherohwo, A. A. Alonge, A. O. Ezekiel and S. O. Samuel, (2023). Effect of the Variation of Atmospheric Refractive Index on Signal Transmission for Digital Terrestrial Television in Jos, Nigeria, *2023 IEEE AFRICON, Nairobi, Kenya*, pp. 1-4, http://dx.doi.org/10.1109/AFRICON55910.2023.10293714

[8]. J.T. Zhimwang, Shaka Oghenemega Samuel, Frank Lagbegha-ebi Mercy, Ibrahim Aminu, and Yahaya Yunisa, (2022). Analysis of Frequency and Polarization Scaling on Rain Attenuated Signal of a KU-Band Link in Jos, Nigeria. *Int. J. Advanced Networking and Applications*. 14(1). https://doi.org/10.35444/IJANA.2022.14111

[9]. J.T. Zhimwang, Shaka Oghenemega Samuel, Frank Lagbegha-ebi Mercy, Ibrahim Aminu, and Yahaya Yunisa, (2022). Categorization of Measured Rainfall Rates and Estimation of their impact on Radio Wave Propagation at Higher Frequency Band (12.5 GHz) in Wukari, Taraba State, *Nigerian Journal of Physics.* 31(2)

[10]. Abayomi, Y., Olusegun, B., & Khamis, N. (2016). Comparative analysis of terrestrial rain attenuation at Ku band for stations in South-Western Nigeria. *International Research Journal of Engineering and Technology,* 3(2), 27-33.

[11]. Igbekele O. J., Zhimwang J.T. and Ogherohwo E. P. (2019). Evaluation of propagation losses due to rain attenuated signal on terrestrial radio links over Jos, Plateau State Nigeria. *Physical science international journal*. 23(1). 1-8 https://doi.org/10.9734/PSIJ/2019/v23i130140

[12]. *Ojo, J. S., Ajewole M. O., & Sarkar S. K. (2008). Rain rate attenuation prediction for satellite communication in Ku and Ka bands over Nigeria. Progress in Electromagnetic Research, 5, 207-223.*

[13]. O. J. Igbekele, B. J. Kwaha, E. P. Ogherohwo and J. T. Zhimwang (2020). Performance Analysis of the Impact of Rain Attenuated Signal on Mobile Cellular Terrestrial Links in Jos, Nigeria. *Physical science international journal*. 24(1). 14-26. https://doi.org/10.9734/PSIJ/2020/v24i130170

[14]. Christofilakis, V., Tatsis, G., Lolis, C.J., Chronopoulos, S. K., Kostarakis, P., Bartzokas, A., Nistazakis, H.E. (2020). A rain estimation model based on microwave signal attenuation measurements in the city of Ioannina, Greece. *Meteorological Application* 27(4), 1-14.

[15]. Nanvyat, N., Mulambalah, C. S., Barshep, Y., Dakul, D. A & Tsingalia, H. M. (2017). Retrospective analysis of malaria transmission patterns and its association with meteorological variables in lowland areas of Plateau state, Nigeria. *International Journal of Mosquito Research*, 4(4), 101-106.

[16]. Michael, W., David, F., & Sophia, Y. (2011). *Physical Science: Concepts in Action; With Earth and Space Science; Weather and Climate.* California: Pearson Prentice Hall.