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Empirical Analysis of Micro-Climatic Effects on Radio Frequency Signal Strength from Base Transceiver Stations in Abraka, Nigeria

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ABSTRACT

Empirical understanding of radio frequency (RF) signal variability under real atmospheric conditions remains critical for the optimization of wireless communication systems in tropical environments. This study investigates the relationship between RF signal strength and key meteorological parameters at operational Base Transceiver Station (BTS) sites in Abraka, Nigeria. Field measurements were conducted over a 28-day period at three BTS locations. RF field strength was recorded at a fixed distance of 100 m and a measurement height of 1.5 m using a Trifield TF2 RF meter, while ambient temperature and relative humidity were obtained from the Nigerian Meteorological agency (NiMet). Descriptive, correlation, and regression analyses were applied to evaluate both overall and site-specific relationships. Overall correlation analysis revealed weak relationships between RF signal strength and temperature ($r = –0.185$, $p = 0.092$) and humidity ($r = 0.105$, $p = 0.343$). However, site-specific analysis demonstrated statistically significant negative correlations between RF signal strength and temperature at two BTS sites ($r = –0.389$, $p = 0.041$; $r = –0.567$, $p = 0.002$), indicating localized atmospheric sensitivity. Multiple regression analysis showed that meteorological parameters explained only 3.5% of total signal variation, highlighting the dominant role of infrastructural and environmental factors. The findings provide localized empirical evidence that is necessary for terrain-aware and climate-resilient wireless network planning in tropical regions and establish a foundation for further studies on diurnal and distance-dependent RF signal behaviour.

INTRODUCTION

Today, technology affects almost all aspects of our lives, and its impact and role cannot be overemphasized. The influence of technology, as it stands today, is immeasurable. Mobile cellular network has an indelible place, and has come to stay (Divya, 2014). The spread of cellular communication into every aspect of our lives, has had a profound impact on society. It has transformed the way we communicate, conduct business, and access information. Mobile devices have become essential instruments for sustaining communication in both personal and professional spheres. Traditional communication barriers have been overcome, permitting instantaneous connectivity across geographical boundaries (Katie, 2025). Reliable radio frequency (RF) signal propagation is fundamental to the performance of contemporary wireless communication networks. In operational environments, RF signals are influenced by a combination of terrain, infrastructure, and atmospheric conditions, with temperature, humidity, atmospheric pressure, and precipitation capable of altering refractivity, absorption, and scattering mechanisms in the troposphere (Luomala, 2014; Sakkas *et al*., 2024).

Recent empirical studies have demonstrated that meteorological factors can directly affect signal attenuation, fading dynamics, and link reliability in both urban and suburban cellular deployments (Amajama *et al*., 2024; Odesanya, 2025; Amajama *et al*. 2025). Tropical environments are particularly sensitive due to high moisture content, elevated thermal gradients, and intense convective activity, which enhance refractive index fluctuations and multipath effects (Song Meng *et al*., 2009; Tanko, 2024). In African operational contexts, several recent studies have reported strong spatial variability in cellular signal strength linked to both meteorological and infrastructural factors. Field studies in Nigeria have demonstrated that local environmental clutter, antenna configuration, and micro-climatic conditions significantly influence received signal levels (Abdulwaheed *et al*. 2024; Adewale *et al*., 2024; Diton, 2025).

Despite these advances, high-resolution, site-specific empirical datasets remain limited in tropical West Africa, particularly for suburban and semi-rural BTS deployments. Most existing work has focused on large-scale drive tests or model-based simulations, leaving a gap in short-range, fixed-site field measurements under realistic operational conditions (Yusuf *et al*., 2024; Jibrin *et al*., 2025). Furthermore, earlier empirical propagation studies in southern Nigeria have shown that distance-dependent path loss and terrain-induced scattering dominate RF behaviour, with atmospheric effects acting as secondary but measurable modifiers (Ohworho, 2023). These findings highlight the need for localized, BTS-level measurements that capture the combined effects of infrastructure and weather in real deployment environments.

This study therefore, presents an empirical assessment of RF signal strength variability in relation to temperature and relative humidity across three operational BTS sites in Abraka, Nigeria. By employing repeated field measurements and site-specific statistical analyses, this work seeks to provide localized evidence to support network planning, optimization, and climate-resilient wireless system design in tropical environments. The remainder of this paper is organized as follows: Section 2 describes the materials and methods, study area, and the measurement design. Section 3 presents the experimental results, including descriptive statistics, correlation, and regression analyses. Section 4 discusses the findings in relation to existing literature and highlights their implications for wireless network planning. Finally, Section 5 concludes the paper and outlines directions for future research.

MATERIALS AND METHODS

Materials

RF signal strength was measured using a Trifield TF2 broadband RF meter, which is suitable for comparative RF field measurements in outdoor environments. The instrument measures aggregate RF field strength across a wide frequency range and is commonly applied in environmental and exposure-based RF studies. While the meter does not provide frequency-selective measurements, it is suitable for assessing temporal variations in received RF power density under consistent measurement geometry. Given that the objective of this study is to examine relative RF signal variation in response to atmospheric conditions rather than spectral or network-level performance, the Trifield TF2 provides an appropriate and reliable measurement platform. Limitations associated with broadband measurement were acknowledged and controlled by maintaining fixed measurement height, distance, and instrument orientation throughout the campaign. Similar broadband field instruments have been widely employed in empirical RF measurement studies for base station environments (Sedara, 2023; Indra, 2024).

Meteorological parameters (ambient temperature and relative humidity) were obtained from NiMet and synchronized with the RF measurements. The use of synchronized meteorological observations in field-based wireless studies is reported in recent literature (Amajama, 2024). The mobile compass app was used to obtain the GPS locations in this study.

Methods

Study area

The study was conducted in Abraka, which is geographically located at approximately latitude 5.7902° N and longitude 6.1047° E in Delta State, southern Nigeria. Abraka is a semi-urban town located in Ethiope East Local Government Area of Delta State, southern Nigeria. The town lies within the tropical rainforest zone and experiences a humid climate with distinct wet and dry seasons. It is intersected by the Ethiope River, which contributes to local microclimatic conditions. The study was conducted at three strategically selected operational base transceiver station (BTS) sites to capture micro-climatic variations, particularly considering their close proximity to one another while also representing typical suburban deployment environments. These sites have been tagged BTS-A (latitude 5.7914ºN, Longitude 6.1719ºE), BTS-B (Latitude 5.7908ºN, Longitude 6.1008ºE) and BTS-C (Latitude 5.7953ºN, Longitude 6.1153ºE). Although the number of sites is limited, each site was monitored intensively over 28 consecutive days, providing a high-resolution dataset suitable for analyzing the influence of temperature and humidity on RF signal strength.

Measurement design

Field measurements were conducted over a 28-day period (26 August – 22 September 2022). RF field strength was measured at a fixed horizontal distance of 100 m from each BTS and at a height of 1.5 m above ground level. Measurements were taken three times at 12:00 noon, and the mean of the three readings was used for analysis. Repeated sampling at fixed spatial positions is consistent with accepted cellular measurement methodologies in recent propagation studies. Studies of atmospheric refractivity and radio propagation show significant diurnal patterns, with refractivity peaking around midday and decreasing in early morning and evening (Omotoso, 2025; Igwe, 2022 and Adamu *et al.*, 2021). Choosing noon measurements allows for analysis under relatively stable atmospheric conditions while minimizing the influence of transitional atmospheric layers present during morning and evening hours.

RESULTS AND DISCUSSION

Descriptive Statistics of RF and Meteorological Parameters

Descriptive statistics were computed to summarize data distributions. Pearson correlation was used to evaluate linear relationships between RF signal strength and meteorological parameters, both on a global and site-specific basis. Multiple linear regression was applied to determine the combined influence of temperature and humidity on signal strength.

Table 1 presents the summary statistics of RF field strength and the associated meteorological variables over the 28-day observation period. RF signal strength exhibited measurable day-to-day fluctuations across the three BTS locations, while ambient temperature and relative humidity showed moderate variability consistent with the tropical climatic conditions of Abraka, Nigeria. The mean and distribution patterns observed provided a baseline for evaluating the influence of short-term atmospheric variations on RF propagation under real operational network conditions.

Table 1: Descriptive statistics of RF signal strength and meteorological parameters (n = 28)

Variable	Mean	SD	Min.	Max.
RF field strength (W/m^2)	5.71	3.55	0.99	14.11
Temperature (°C)	26.31	1.94	23.60	29.50
Relative humidity (%)	82.88	8.31	62.00	93.00

The descriptive statistics show that RF field strength ranged from 0.99 to 14.11 W/m^2 (mean = 5.71, SD = 3.55). Ambient temperature ranged from 23.60 to 29.50 °C (mean = 26.31, SD = 1.94), while relative humidity ranged from 62.00% to 93.00% (mean = 82.88%, SD = 8.31).

Table 2: Site-specific descriptive statistics of RF signal strength and meteorological parameters

BTS Site	RF Mean (W/m^2)	RF SD	RF Min.	RF Max.	Temp Mean (°C)	Temp. SD	Temp. Min.	Temp. Max	Humid. Mean (%)	Humid. SD	Humid. Min.	Humid. Max.
Site A	6.17	1.75	3.26	9.99	26.20	1.91	23.60	29.20	83.14	8.09	65	93
Site B	1.75	0.49	0.99	2.88	26.35	1.99	23.70	29.50	82.82	8.53	62	93
Site C	9.22	2.48	3.73	14.11	26.37	2.00	23.70	29.50	82.68	8.60	62	93

Site-specific descriptive statistics (Table 2) revealed marked differences in RF field strength across the three BTS locations. Site C exhibited the highest mean RF signal strength (9.22 W/m^2), followed by Site A (6.17 W/m^2), while Site B recorded substantially lower average levels (1.75 W/m^2). In contrast, ambient temperature and relative humidity showed minimal variation across sites, with comparable mean temperatures (≈26.3 °C) and relative humidity values (≈83%). These findings indicate that inter-site differences in RF signal strength are primarily driven by infrastructural and environmental factors rather than spatial variability in meteorological conditions.

Temporal Variation of RF Signal Strength

Figure 1 illustrates the daily variation of RF signal strength measured at 100 m from the BTS sites over the study duration. The figure shows temporal fluctuations that suggest dynamic short-term influences on signal behaviour. Although the RF levels remained broadly stable, noticeable day-to-day variations were present, indicating the combined effects of environmental and infrastructural factors.

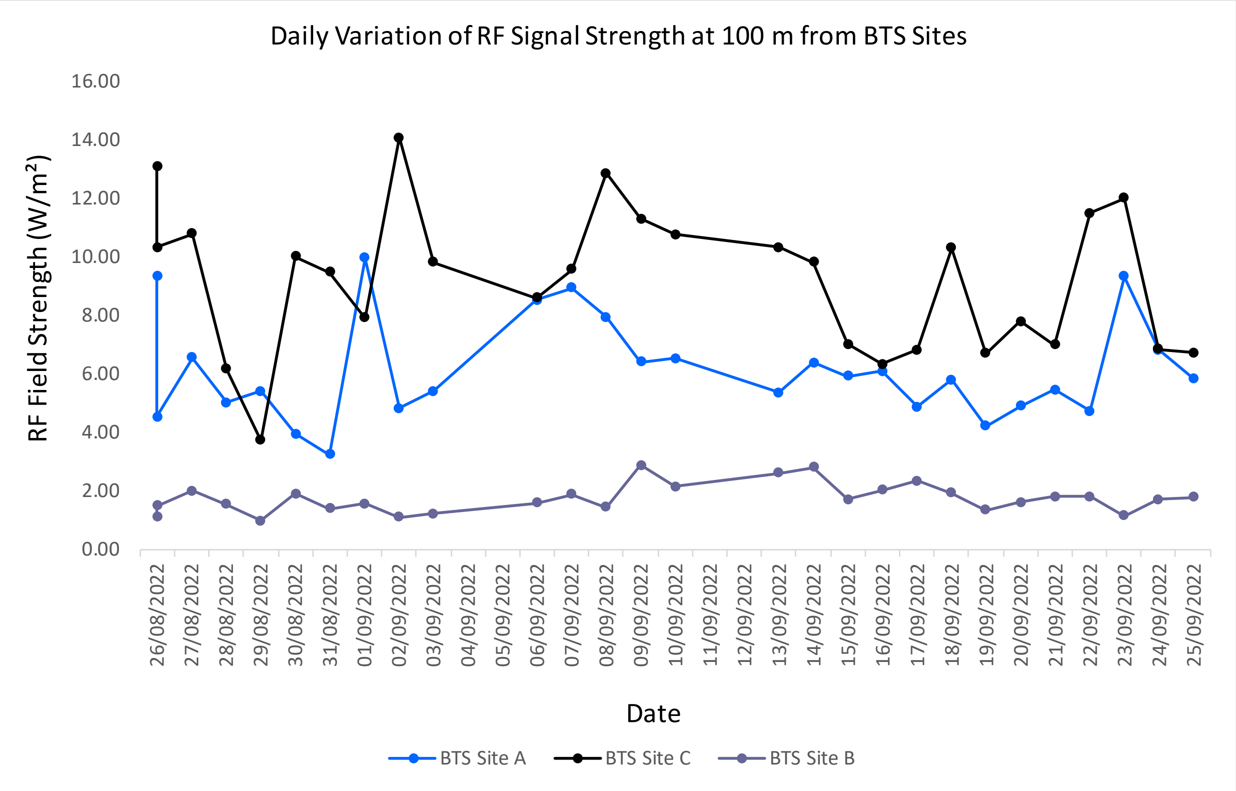

Figure 1: Daily variation of RF field strength measured at 100 m from three BTS sites in Abraka, Nigeria over the 28-day measurement period.

Overall Correlation Between RF Signal Strength and Weather Parameters

Pearson correlation analysis was first conducted using the combined dataset from all BTS sites to assess the general relationship between RF signal strength and meteorological factors. A weak negative correlation was observed (Table 3) between RF signal strength and ambient temperature (r = –0.185, p = 0.092), while a very weak positive correlation was found between RF signal strength and relative humidity (r = 0.105, p = 0.343). These relationships were not statistically significant at the 0.05 level, suggesting that temperature and humidity alone exert limited direct influence on RF variation when analyzed in aggregate.

Table 3: Overall Pearson Correlation Between RF Signal Strength and Meteorological Variables

Parameter Pair	r	p-value
RF vs Temperature	–0.185	0.092
RF vs Humidity	0.105	0.343

Site-Specific Correlation Analysis

To examine localized propagation behaviour, site-specific Pearson correlation analyses were performed for each BTS location (Table 4). The results revealed substantial inter-site variability.

At Site A, RF signal strength showed a moderate negative and statistically significant relationship with ambient temperature (r = –0.389, p = 0.041), indicating measurable temperature-dependent attenuation. A moderate positive but non-significant relationship with relative humidity was observed (r = 0.344, p = 0.073). At Site B, both temperature and humidity exhibited weak and statistically non-significant associations with RF signal strength, suggesting limited atmospheric sensitivity at this location. At Site C, a strong negative and statistically significant relationship was observed between RF signal strength and temperature (r = –0.567, p = 0.002), highlighting a pronounced sensitivity of this site to thermal conditions.

Table 4: Site-specific Pearson correlation coefficients

BTS Site	RF vs Temp. (r)	p-value	RF vs Humidity (r)	p-value
Site A	-0.389	0.041	0.344	0.073
Site B	0.175	0.374	-0.167	0.395
Site C	-0.567	0.002	0.267	0.170

Figures 2 and 3 visually depict these inter-site variations using multi-series scatter plots.

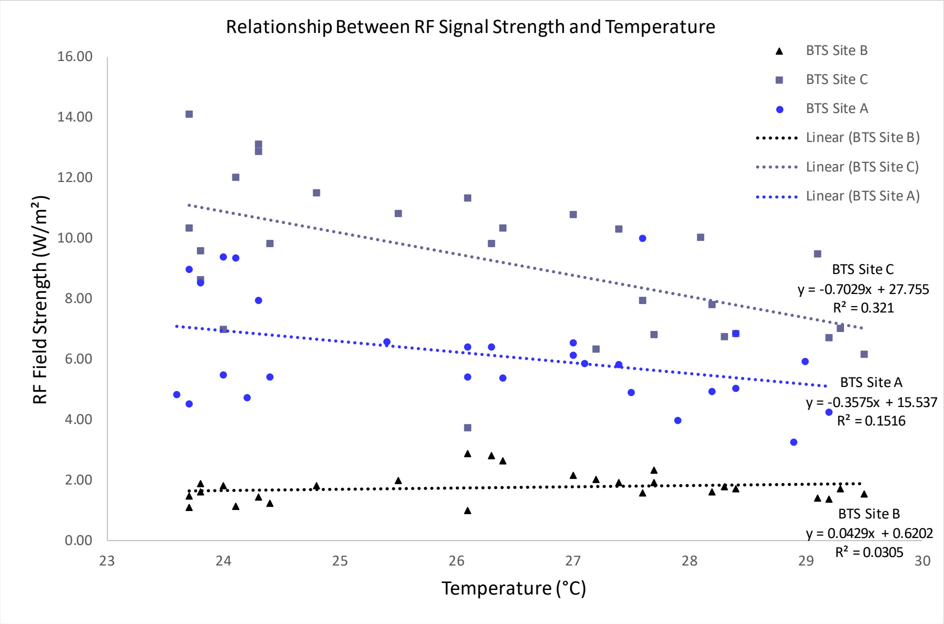

Figure 2: Scatter plot showing the relationship between RF signal strength and ambient temperature, with linear regression fit for the three BTS sites.

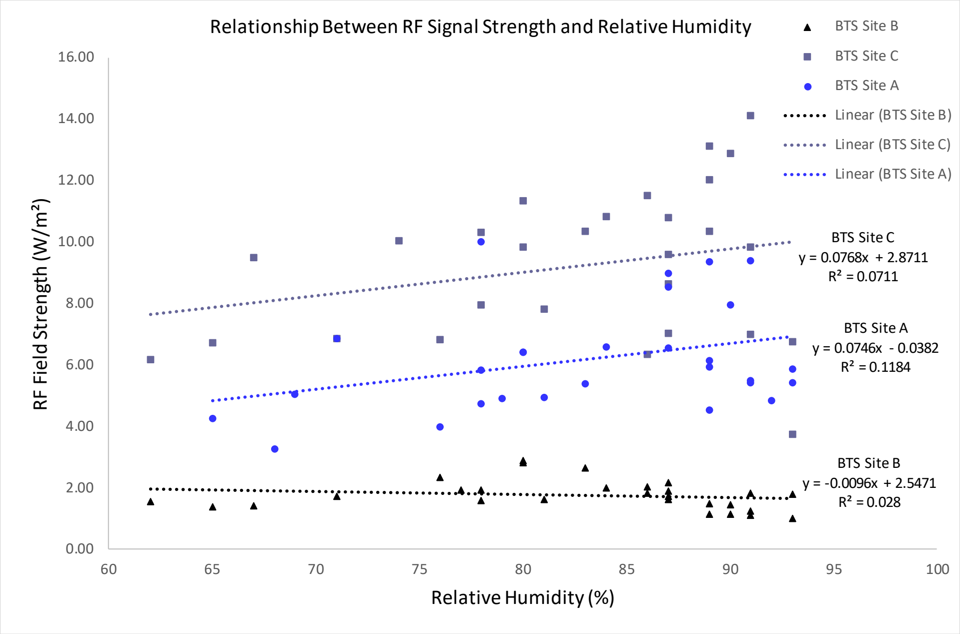

Figure 3: Scatter plot illustrating the relationship between RF signal strength and relative humidity with linear regression trendline.

Regression Analysis

Multiple linear regression analysis was conducted to evaluate the combined influence of temperature and relative humidity on RF signal strength. The derived model is:

$$RF = 17.789 - 0.397\ (\text{Temperature}) - 0.020\ (\text{Humidity}) \quad (1)$$

The regression model produced a low coefficient of determination, ($R^2 = 0.035$, shown in Table 5), indicating that only approximately 3.5% of the variation in RF signal strength was explained by the combined meteorological parameters. This low explanatory power suggests that factors beyond atmospheric conditions - including distance-related attenuation, multipath fading, antenna orientation, terrain effects, and BTS traffic load - play dominant roles in practical BTS environments.

Table 5: Multiple linear regression summary (RF as dependent variable)

Parameter	Coefficient
Intercept	17.789
Temperature	–0.397
Humidity	–0.020
R^2	0.035

Distribution of RF Signal Strength Across BTS Sites

Figure 4 presents a comparative visualization of RF signal strength distributions across the three BTS sites. The box-and-whisker plot reveals clear inter-site variability, supporting the statistical evidence of localized influences on signal propagation.

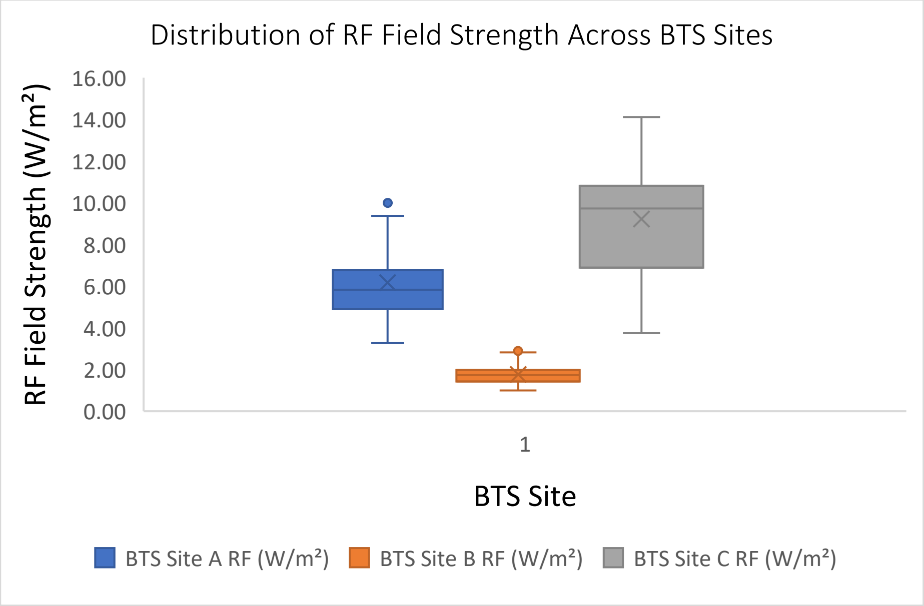

Figure 4: Distribution of RF signal strength across BTS sites.

Discussion

The results demonstrate that RF signal strength at BTS sites in Abraka is only weakly influenced by meteorological parameters when analyzed in aggregate, confirming observations reported in recent cellular propagation studies in tropical and subtropical regions (Diton, 2025). Studies in Nigeria and other developing regions have similarly reported that temperature and humidity often play secondary roles relative to terrain, multipath effects, and infrastructural configurations (Amajama, 2025; Adamu, 2021; Nemah *et al.*, 2021).

The statistically significant temperature-dependent attenuation observed at Sites A and C aligns with recent findings from tropospheric refractivity studies, which have shown that thermal gradients strongly influence radio-wave bending and fading under humid tropical conditions. (Tanko *et al.*, 2024; Akpootu, *et al.*, 2024). At Site B, the absence of significant weather dependence suggests that local infrastructural and terrain-induced effects, such as obstruction, diffraction, reflection, scattering and shadowing, dominate signal behaviour. Similar site-specific heterogeneity has been documented in large-scale LTE network assessments in Nigeria and other African urban environments (Luomala, *et al.*, 2014, Ashidi, 2025; Yusuf *et al.*, 2024).

The low explanatory power of the regression model further corroborates recent findings that meteorological parameters alone are insufficient to predict real-world RF signal variations in operational cellular networks. Drive-test and predictive modelling studies have emphasized the dominant influence of network topology, clutter loss, and dynamic traffic loading. (MohammedJava *et al.*, 2025).

Overall, this study complements earlier studies by demonstrating that while distance and environmental obstructions dominate attenuation, localized meteorological modulation is measurable and site-dependent.

CONCLUSION

This study presented an empirical assessment of RF signal strength variability in relation to meteorological parameters at three operational BTS sites in Abraka, Nigeria. The findings demonstrated that while ambient temperature and relative humidity exert measurable influence on RF propagation, their direct effects are generally weak when evaluated in aggregate. The overall correlation analysis revealed only weak relationships between RF signal strength and both temperature and relative humidity. These results suggest that short-term atmospheric variations alone are insufficient to explain the majority of RF signal fluctuations in practical urban and suburban deployment scenarios. This observation is consistent with established radio propagation theory, which identifies multipath fading, diffraction, and local obstructions as dominant drivers of signal variability in terrestrial microwave and cellular links (John, 2005).

Site-specific analysis, however, revealed pronounced localized behaviour. Two of the studied BTS sites exhibited statistically significant temperature-dependent signal attenuation, highlighting the importance of micro-environmental and infrastructural characteristics - antenna orientation, building density, vegetation density, surface reflectivity - in modulating the meteorological influence on RF propagation. The low coefficient of determination of the regression model further reinforces that non-atmospheric factors - including terrain features, multipath propagation, antenna configuration, and network traffic dynamics - dominate RF signal behaviour in practical deployments.

Overall, the findings of this study contribute valuable localized empirical data to the limited body of propagation studies in tropical environments and provide practical insights for wireless network planning and optimization. The evidence of site-dependent sensitivity underscores the need for context-specific network design rather than reliance solely on generalized propagation models.

While this study covers only three BTS sites, the detailed, continuous measurements provide valuable insights into micro-climatic effects on RF signal propagation. Limitations include the short-term monitoring period and the restricted number of sites, which may affect generalizability. Future work could expand the number of sites, extend the monitoring period, and incorporate additional meteorological and infrastructural parameters to improve understanding of RF signal variability across broader tropical regions.

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