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The Effect of Fog-Induced Attenuation for Optimum Performance in Communication Links in Lagos, Nigeria

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Abstract

This study investigates the impact of fog-induced attenuation on the performance of free-space optical (FSO) communication systems, with a focus on Lagos, Nigeria. Using meteorological data from the Visual Crossing archive spanning 2010 to 2021, attenuation levels at 850 nm and 1550 nm wavelengths were analyzed. The results indicate that the 850 nm wavelength experiences significantly higher attenuation due to fog compared to 1550 nm. Peak attenuation was observed in December and January, with values of 3.50 dB/km and 2.79 dB/km respectively at 850 nm, and 2.08 dB/km and 1.55 dB/km at 1550 nm. These findings highlight the superiority of the 1550 nm wavelength for FSO communication in fog-prone environments, owing to its lower scattering losses, reduced absorption, and better atmospheric penetration. The study emphasizes the importance of wavelength selection and adaptive communication techniques to improve system reliability under varying weather conditions. The analysis offers practical guidance for enhancing FSO system performance and contributes to the broader understanding of atmospheric effects on optical communication links.

Keywords: Free-Space Optics (FSO), Fog-Induced Attenuation, Wavelength Selection, Optical Communication, Microwave frequency

1. Introduction

Communication systems play a critical role in modern society, enabling the transfer of data, voice, and multimedia across vast distances. However, environmental factors such as fog can significantly impact their performance. Fog-induced attenuation, resulting from scattering and absorption by suspended water droplets, poses a major challenge—particularly for wireless and free-space optical (FSO) systems (Andrews & Phillips, 2005).

FSO systems transmit high-bandwidth optical signals through the atmosphere, but their reliability is severely affected by fog, which can cause attenuation exceeding 100 dB/km in extreme conditions. This is well beyond typical fade margins of 20–30 dB (Scott Bloom, 2003). The degree of attenuation depends on fog density, droplet size, and signal wavelength. Higher frequencies suffer greater losses, and fog particles—being similar in size to optical wavelengths—act as strong scatterers in the Mie regime (Kim & Korevaar, 2001); (Kahn, 2002).

The attenuation coefficient β_{fog} can be estimated using empirical models based on visibility. One widely used model is the Kim model, which expresses fog attenuation as:

$$\beta_{\text{fog}} = 3.91 \left(\frac{\lambda}{550}\right)^{-p} \cdot \frac{1}{V} \quad \text{eq 1}$$

Where:

- **λ** is the wavelength (nm),
- **V** is the visibility range (km),
- **P** is the size distribution coefficient, determined as:

$$p = \begin{cases} 1.6 & \text{if } V > 50 \\ 1.3 & \text{if } 6 < V \leq 50 \\ 0.16V + 0.34 & \text{if } 1 < V \leq 6 \\ V - 0.5 & \text{if } 0.5 < V \leq 1 \\ 0 & \text{if } V < 0.5 \end{cases}$$

Understanding and applying these models is essential for predicting signal loss and improving the design and reliability of communication systems under foggy conditions. This research investigates fog-induced attenuation in free-space links, with a focus on quantifying its effects and proposing mitigation strategies to enhance signal robustness in adverse weather (Majumdar & Ricklin, 2008).

BACKGROUND TO STUDY

In Lagos, Nigeria, a coastal city characterized by high humidity, dense population, and varying weather patterns—fog events, though not as frequent as in temperate regions, can still significantly affect free-space optical (FSO) communication systems. The impact of fog-induced attenuation in this region is most notable during the early hours of the day, particularly in the rainy season and occasionally during the harmattan period (Falodun et al., 2020; Shaina & Gupta, 2016), when atmospheric moisture is high and visibility drops sharply. The fog observed in Lagos primarily resembles radiation and advection fog, which are influenced by local climatic conditions such as overnight cooling, residual moisture from rainfall, and

Comparative Analysis of Free Space Optical Communication System for Various Optical Transmission Windows under Adverse Weather Conditions. Radiation fog often forms in low-lying inland parts of Lagos during the early mornings when the ground cools rapidly under clear skies after rainfall. The retained soil moisture increases dew point levels, allowing the air near the ground to become saturated. This leads to the formation of dense fog layers with small water droplets that scatter and absorb infrared optical signals. This scattering, typically in the Mie regime due to the size of the droplets, can cause significant signal attenuation, particularly for high-frequency FSO links (Ojo et al., 2019).

Advection fog, though less frequent, may develop when warm, moist air from the Atlantic Ocean moves inland and meets the cooler urban surfaces of Lagos, especially at night or early morning. This type of fog tends to be thicker and more widespread, contributing to higher levels of signal degradation due to the presence of larger fog droplets, which increase both absorption and scattering of light. In densely built-up areas, this effect is amplified by heat retention and local wind patterns, reducing visibility and affecting the quality and availability of optical links (Shaina & Gupta, 2016).

Fog-related attenuation in Lagos can exceed typical system fade margins, leading to signal outages or degradation, especially for links with narrow fade tolerances. Attenuation values in dense fog conditions may reach critical thresholds—often beyond 100 dB/km (Esmail et al., 2016). Jeopardizing the stability of FSO systems. To quantify and predict this attenuation, visibility-based empirical models such as the Kim model are commonly used. The Kim model estimates fog-induced attenuation using the formula:

$$\beta_{\text{fog}} = 3.91 \left(\frac{\lambda}{550} \right)^{-p} \cdot \frac{1}{V}$$

eq 2

Understanding how local fog conditions affect signal propagation is essential for the design and deployment of resilient FSO networks in Lagos. Techniques such as spatial diversity, error correction, and the use of optical amplifiers like Erbium-Doped Fiber Amplifiers (EDFA) can mitigate fog-related losses (Yasir et al., 2022). Deploying multiple transmitters and receivers improves signal reception during periods of low visibility by reducing the probability of simultaneous attenuation across all paths. As Lagos continues to expand its digital infrastructure, ensuring the reliability of high-speed communication links—especially those using FSO technology—requires a proactive approach to modeling, predicting, and managing fog-induced attenuation in its unique coastal environment.

DATA AND METHOD OF ANALYSIS

Lagos (6.4541°N, 3.3947°E; 1,171.28 km²; 320 m elevation) is highly susceptible to fog due to its coastal location (Falodun et al., 2020). A dataset from Visual Crossing (2010–2021) provided daily measurements of temperature, dew point, humidity, rainfall, wind metrics, pressure, and visibility. Data was cleaned and statistically processed using Excel and Minitab.

Descriptive statistics and monthly trend lines showed high fog density during the wet season, corresponding with low visibility and increased signal attenuation. The Kim–Ijaz model was used to estimate attenuation based on visibility and wavelength (Ijaz et al., 2013).

A multiple linear regression was performed in Minitab:

- Dependent variables: attenuation at 850 nm and 1550 nm.
- Independent variables: temperature, humidity, pressure, visibility.

The cleaned dataset was then imported into Minitab for multiple linear regression analysis, with attenuation at both 850 nm and 1550 nm wavelengths as the dependent variables, and temperature, humidity, pressure, and visibility as the independent variables. The regression output provided coefficients and significance tests (t-tests, F-tests), alongside performance metrics like R-squared and standard error. These results helped identify the dominant meteorological factors contributing to attenuation in Lagos' coastal urban context.

Furthermore, the characteristics of key atmospheric parameters—visibility, humidity, pressure, and temperature—were evaluated for their roles in signal degradation. Visibility, in particular, emerged as the most influential factor, as fog reduces horizontal transparency due to suspended water droplets that scatter infrared signals. Dense fog conditions in Lagos, though episodic, can reduce visibility below 1 km and cause attenuation exceeding the fade margin of typical FSO systems, leading to outages. The International Visibility Code (IVC) was referenced to classify various visibility thresholds and their corresponding attenuation values, reinforcing the relevance of this variable in attenuation modeling.

Humidity contributes significantly to fog formation and directly affects the scattering and absorption of signals. Lagos' typically high humidity, especially in coastal areas and during the early morning, enhances fog density and droplet formation, compounding attenuation. Pressure fluctuations influence condensation rates and the formation of fog layers, with lower pressures creating favorable conditions for droplet accumulation. Similarly, temperature particularly when it drops to the dew point acts as a catalyst for fog development. Temperature inversions, common in Lagos' humid nights, can trap cooler air near the ground, allowing fog to persist and cause prolonged signal degradation.

In summary, the integration of long-term atmospheric data, empirical modeling using the Kim-Ijaz formula, and multivariate regression analysis offered a comprehensive framework to quantify and understand fog-induced attenuation in Lagos. This approach ensures that the findings are not only theoretically sound but also practically applicable to communication system design in the city's dynamic urban and coastal environment.

RESULTS AND DISCUSSION

Regression Analysis for Fog-Induced Attenuation.

To conduct a thorough investigation of the impact of fog-induced attenuation on communication links, we made use of data covering the years 2010 to 2021. This large dataset offered a solid basis for examining a variety of environmental factors and how they affect the performance of communication links. The dataset was sourced from Visual Crossing (VC), covering key environmental parameters such as Temperature (TEMP), Humidity (HUM), Pressure (PRE), and Visibility (VIS). In general, the results show that there is a positive relationship between the two wavelengths 1550 nm and 850 nm respectively during the study period.

Regression Analysis at 850 nm

The derived model:

$$AER_{850} = 4.16 - 0.03057\,TEMP - 0.016404\,HUM - 0.00091\,PRE - 0.08978\,VIS$$

Key findings:

- Visibility is most influential (β = –0.08978, p < .001).
- Temperature (β = –0.03057, p < .001) and humidity (β = –0.016404, p < .001) also reduced attenuation.
- Pressure had no significant effect (p = .573).
- R^2 = 68.90%, adj R^2 = 68.87%: strong explanatory power.

Regression Analysis at 1550 nm

The model:

$$AER_{1550} = 22.47 - 0.08857\,TEMP - 0.04558\,HUM - 0.01402\,PRE + 0.08992\,VIS$$

Impact on Communication Links

Fog-induced attenuation (>100 dB/km) drastically reduces link range (especially for 500 m–4 km FSO links), increases error rates, lowers throughput, and causes signal fading—directly threatening reliability (Andrews & Phillips, 2005; Bloom et al., 2003). Adaptive techniques such as redundancy, error correction, and real-time adjustments are essential for preserving link integrity in fog-prone environments.

In the year 2010 (Figure 2a), significant seasonal fluctuation was observed in the aerosol optical thickness at 850 nm and 1550 nm, with maxima in January at 1.39 dB/Km and December at 1.42 dB/Km for 850 nm, and 0.60 dB/Km in both January and December for 1550 nm. At 550 nm, the optical thickness was consistently higher, indicating that visible light was more attenuated than infrared light. This implies better performance and reliability when using 1550 nm wavelengths.

The data for 2011 (Figure 2b) showed similar seasonal patterns, with maximum aerosol optical thickness at 2.79 dB/Km in January and 1.67 dB/Km in December for the 850 nm wavelength. At 1550 nm, values were 0.71 dB/Km in January and 0.78 dB/Km in December. This consistent difference confirms the advantage of infrared communication under foggy conditions.

In 2012 (Figure 2c), early and late months exhibited higher optical thickness, consistent with increased fog density. At 850 nm, attenuation reached 2.06 dB/Km in January and 1.28 dB/Km in December. At 1550 nm, it was lower: 1.04 dB/Km in January and 0.53 dB/Km in December, reaffirming the benefit of IR wavelengths.

The 2013 analysis (Figure 2d) continued this trend. At 850 nm, attenuation was 1.45 dB/Km in January and 1.09 dB/Km in December, while at 1550 nm, it was 0.64 dB/Km and 0.42 dB/Km respectively. This highlights the vulnerability of visible light and supports the need for IR-based FSO systems.

In 2014 (Figure 2e), peak attenuation again occurred in January (1.13 dB/Km) and December (1.31 dB/Km) at 850 nm. At 1550 nm, values were 0.44 dB/Km in January and 0.55 dB/Km in December. The year’s data reinforced previous conclusions regarding the superiority of 1550 nm signals in foggy environments.

During 2015 (Figure 2f), visible light communication was further challenged. Attenuation at 850 nm peaked at 0.95 dB/Km in January and 3.50 dB/Km in December. At 1550 nm, values were 0.34 dB/Km in January and 2.08 dB/Km in December. Despite high fog density, infrared consistently performed better.

In 2016 (Figure 2g), January saw 2.16 dB/Km attenuation at 850 nm and December 1.53 dB/Km. At 1550 nm, January recorded 1.10 dB/Km, and December 0.69 dB/Km. The substantial difference in optical thickness persisted, justifying wavelength optimization for FSO links.

The 2017 dataset (Figure 2h) showed 1.51 dB/Km attenuation at 850 nm in January and 1.72 dB/Km in December. At 1550 nm, attenuation remained lower, validating the choice of this band for consistent performance in Lagos' foggy seasons.

In 2018 (Figure 2i), January recorded 1.96 dB/Km and December 2.11 dB/Km at 850 nm, while 1550 nm saw 0.97 dB/Km and 1.07 dB/Km respectively. These findings align with the trend of higher fog interference in the visible band and underscore the reliability of infrared.

For 2019 (Figure 2j), peak values at 850 nm were 1.48 dB/Km in January and 1.33 dB/Km in December. At 1550 nm, they were 1.47 dB/Km and 0.56 dB/Km respectively. These values confirmed the pattern and underscored the consistency of fog-induced attenuation patterns over time.

In 2020 (Figure 2k), January showed 2.68 dB/Km at 850 nm and December 0.87 dB/Km. 1550 nm values were 1.47 dB/Km and 0.30 dB/Km. The wide margin once again highlighted the limitations of visible spectrum-based communication systems.

Finally, in 2021 (Figure 2l), 850 nm had attenuation of 1.19 dB/Km in January and 1.58 dB/Km in December. At 1550 nm, attenuation stood at 0.48 dB/Km and 0.72 dB/Km respectively. This year capped the decade-long pattern, reinforcing the recommendation to prioritize 1550 nm communication links in Lagos' fog-prone periods.

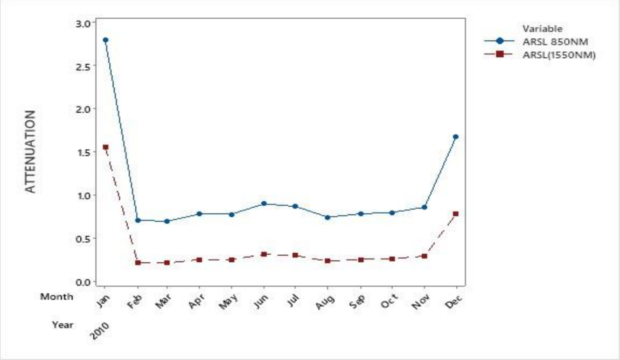

Figure 2a: Aerosol Attenuation of 850nm and 1550nm in the Year 2010

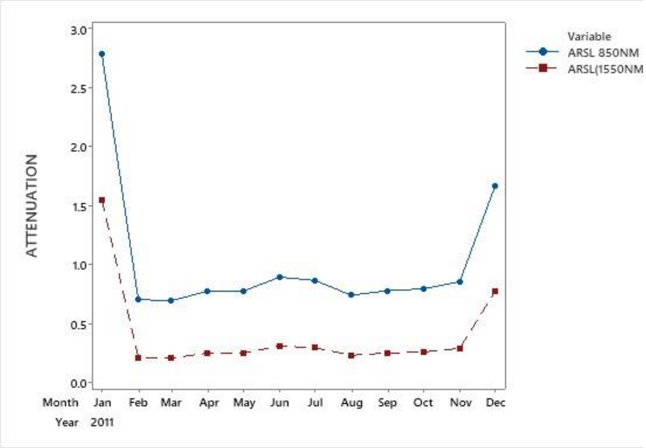

Figure 2b: Aerosol Attenuation of 850nm and 1550nm in the Year 2011

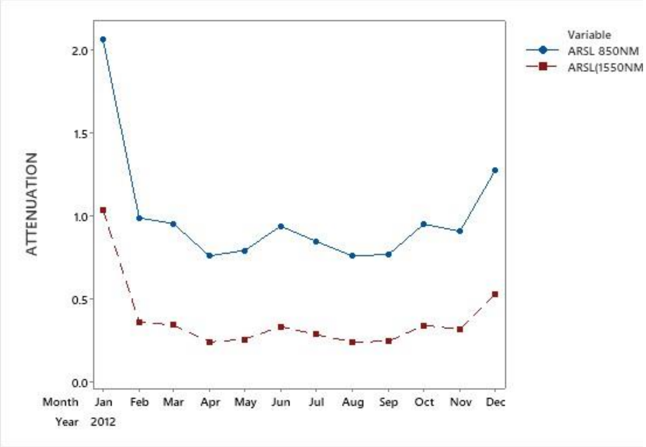

Figure 2c: Aerosol Attenuation of 850nm and 1550nm in the Year 2012

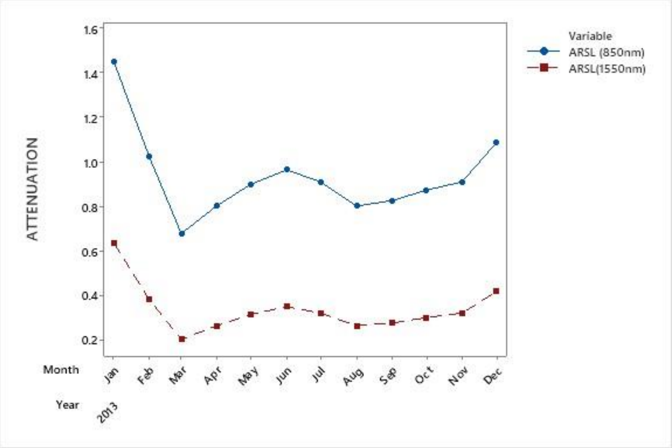

Figure 2d: Aerosol Attenuation of 850nm and 1550nm in the Year 2013

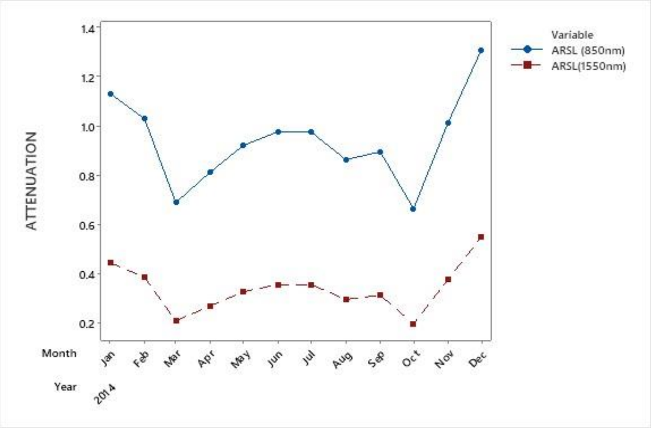

Figure 2e: Aerosol Attenuation of 850nm and 1550nm in the Year 2014

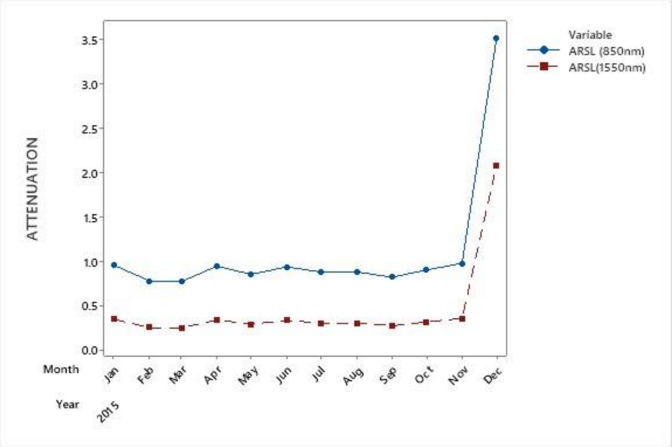

Figure 2f: Aerosol Attenuation of 850nm and 1550nm in the Year 2015

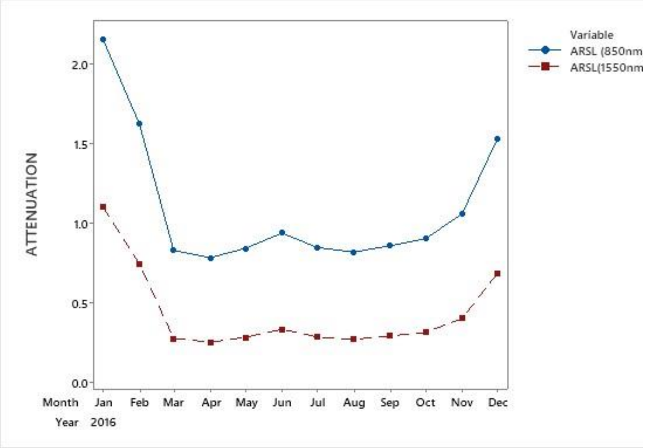

Figure 2g: Aerosol Attenuation of 850nm and 1550nm in the Year 2016

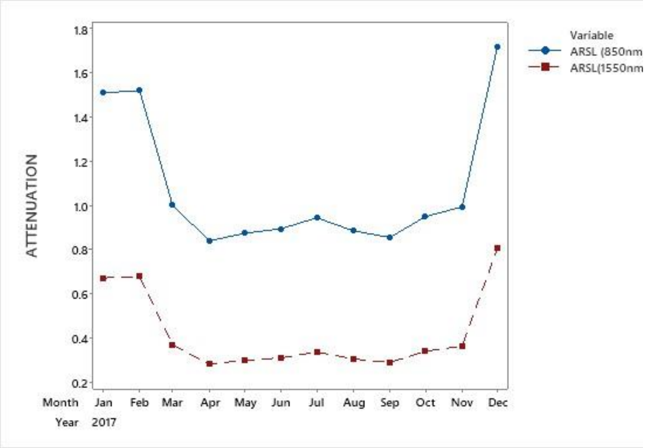

Figure 2h: Aerosol Attenuation of 850nm and 1550nm in the Year 2017

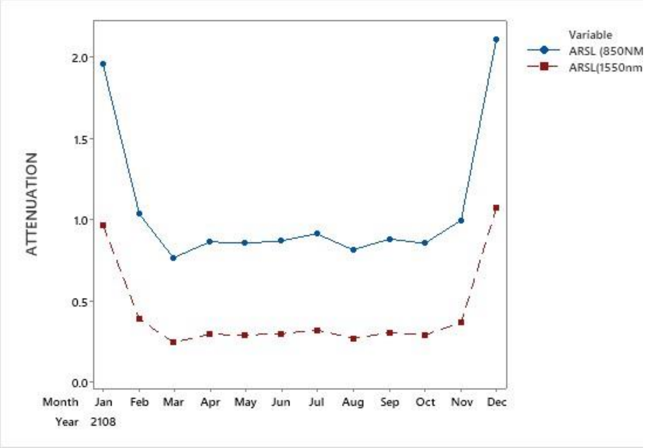

Figure 2i: Aerosol Attenuation of 850nm and 1550nm in the Year 2018

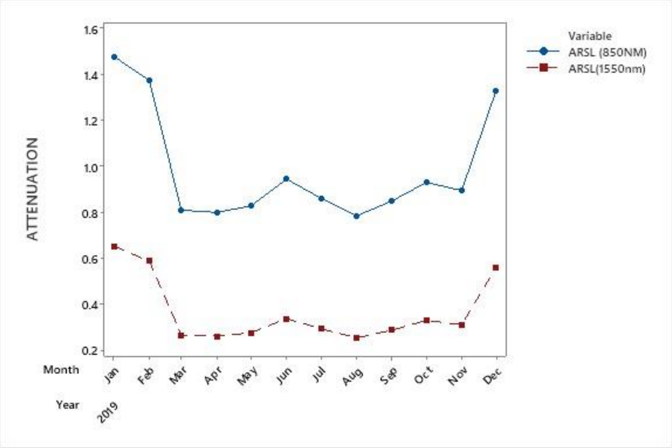

Figure 2j: Aerosol Attenuation of 850nm and 1550nm in the Year 2019

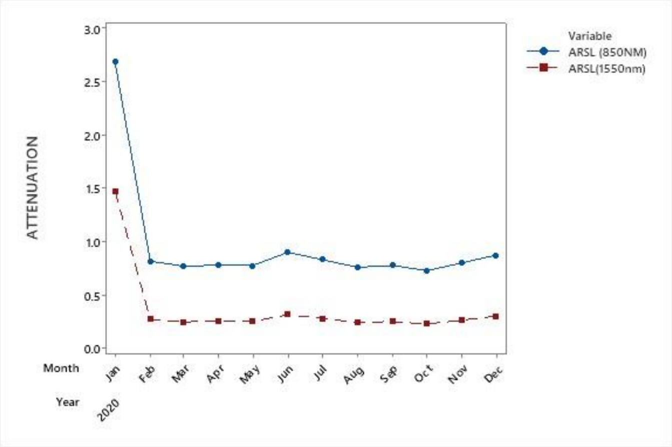

Figure 2k: Aerosol Attenuation of 850nm and 1550nm in the Year 2019

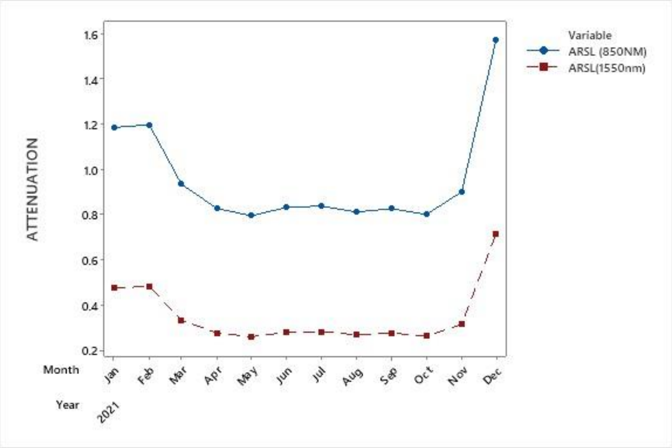

Figure 2l: Aerosol Attenuation of 850nm and 1550nm in the Year 2020

REGRESSION ANALYSIS FOR FOG-INDUCED ATTENUATION

Attenuation at 850 nm

The multiple linear regression analysis performed using Minitab revealed that temperature (TEMP), humidity (HUM), and visibility (VIS) significantly influence attenuation at 850 nm, while pressure (PRE) does not. The regression equation is:

AER (850 nm) = 4.16 - 0.03057TEMP - 0.016404HUM - 0.00091PRE - 0.08978VIS

This equation reveals a negative relationship between environmental variables and attenuation, meaning higher values of TEMP, HUM, and VIS result in lower attenuation. Notably:

- Each 1°C rise in temperature reduces attenuation by 0.03057 dB/km.
- Each 1% increase in humidity reduces attenuation by 0.016404 dB/km.
- Each 1 km improvement in visibility reduces attenuation by 0.08978 dB/km.

These results highlight visibility as the most influential factor in fog-induced attenuation. The model's high R-squared (68.90%) and adjusted R-squared (68.87%) demonstrate strong predictive power.

Practical Implications: Communication systems like FSO and microwave can leverage this model for adaptive performance, using real-time environmental inputs to dynamically adjust transmission parameters. Since pressure shows negligible effect, it can be excluded from predictive models to streamline computations.

Comparison with Literature:

- Visibility's impact agrees with prior studies.
- Temperature’s inverse correlation confirms existing findings.
- The humidity effect offers a novel insight: high humidity in fog may lead to larger droplets with less scattering impact.

Outliers & Residuals: Some observations showed high residuals, indicating the model’s limitations under extreme conditions—useful for further research.

Table 1: Regression Coefficients at 850 nm

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	4.16	1.66	2.50	0.012	
TEMP	-0.03057	0.00230	-13.29	0.000	1.87
HUM	-0.016404	0.00051	-32.21	0.000	1.64
PRE	-0.00091	0.00161	-0.56	0.573	1.49
VIS	-0.08978	0.00144	-62.53	0.000	1.34

Table 2: Model Summary at 850 nm

S	R-sq	R-sq(adj)	R-sq(pred)
0.157675	68.90%	68.87%	68.49%

Table 3: ANOVA

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	229.284	57.3210	2305.63	0.000
TEMP	1	4.389	4.3886	176.52	0.000
HUM	1	25.788	25.7877	1037.26	0.000
PRE	1	0.008	0.0079	0.32	0.573
VIS	1	97.217	97.2165	3910.35	0.000
Error	4162	103.473	0.0249		
Total	4166	332.757			

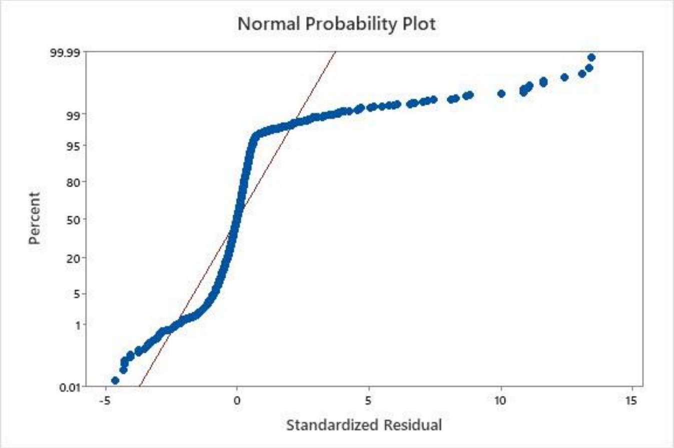

Figure 3a: Normal Probability Plot at 850 nm

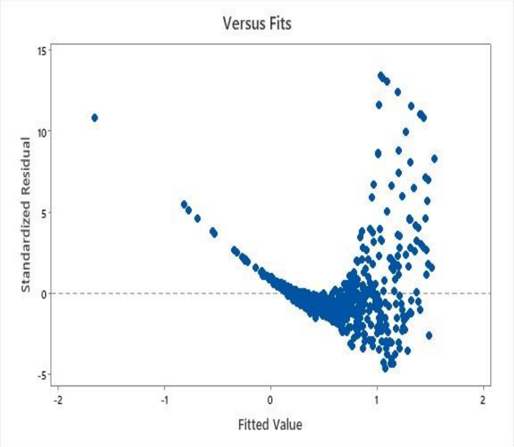

Figure 3b: Versus Plot

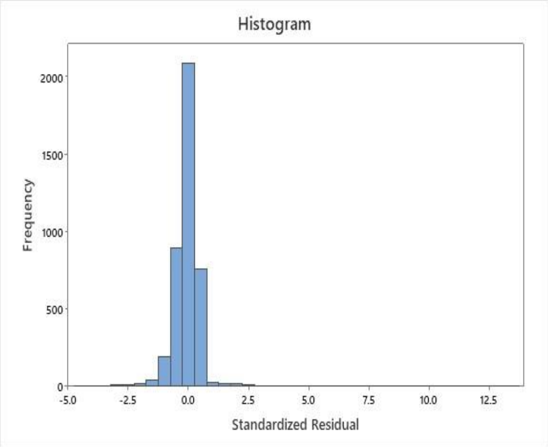

Figure 3c: Histogram Plot at 850 nm

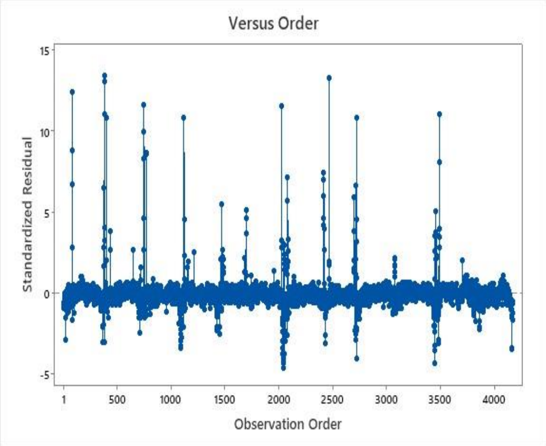

Figure 3d: Versus Order Plot at 850 nm

Attenuation at 1550 nm

The regression analysis at 1550 nm evaluated how temperature, humidity, pressure, and visibility affect signal attenuation in Lagos, Nigeria. The regression equation is:

AER (1550 nm) = 22.47 - 0.08857TEMP - 0.04558HUM - 0.01402PRE + 0.08992VIS

Key insights:

- Higher temperature reduces attenuation by 0.08857 dB/km.
- Humidity inversely affects attenuation by 0.04558 dB/km.
- Pressure also reduces attenuation slightly by 0.01402 dB/km.
- Visibility *increases* attenuation by 0.08992 dB/km—likely due to lower scattering in clearer conditions increasing direct absorption.

Model Utility: The equation serves as a valuable tool for real-time adaptation in FSO systems. During low temperature and high humidity periods, signal loss is naturally minimized.

Table 4: Coefficients at 1550 nm

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	22.47	5.61	4.01	0.000	
TEMP	-0.08857	0.00776	-11.42	0.000	1.87
HUM	-0.04558	0.00172	-26.55	0.000	1.64
PRE	-0.01402	0.00542	-2.59	0.010	1.49
VIS	0.08992	0.00484	18.58	0.000	1.34

Table 5: ANOVA at 1550 nm

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	211.60	52.901	187.21	0.000
TEMP	1	36.83	36.828	130.33	0.000
HUM	1	199.13	199.13	704.67	0.000
PRE	1	1.89	1.893	6.70	0.010
VIS	1	97.51	97.510	345.07	0.000
Error	4162	1176.11	0.283		
Total	4166	1387.71			

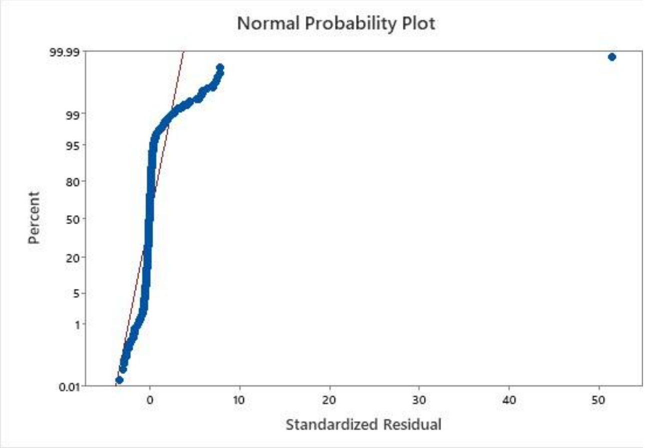

Figure 3e: Normal Probability Plot at 1550nm

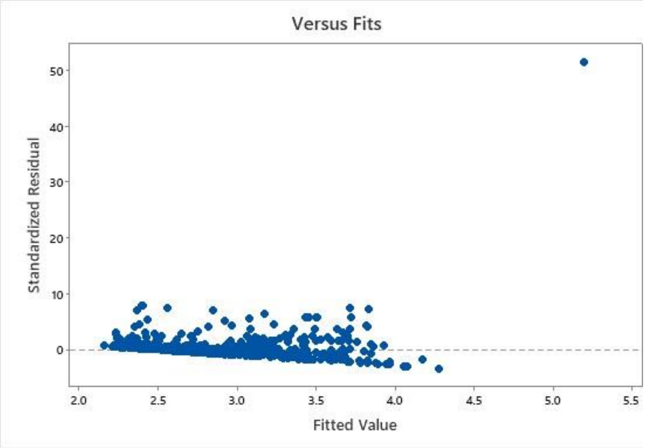

Figure 3f: Versus Fits at 1550 nm

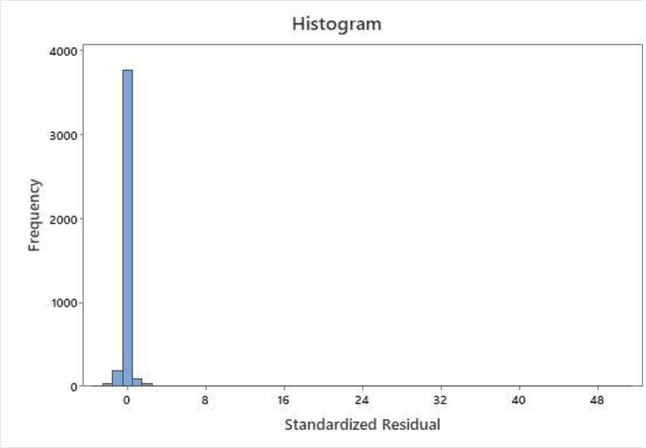

Figure 3g: Histogram at 1550 nm

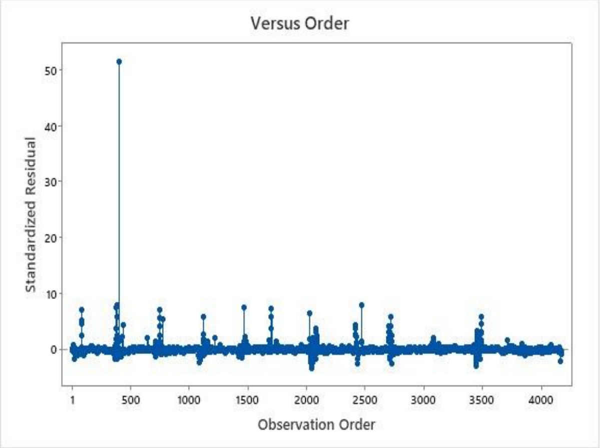

Figure 3h: Versus Order Plot at 1550 nm

Impact and Significance on Communication Links

Results demonstrated strong performance ($R^2 \approx 0.69$) with visibility, temperature, and humidity as key factors. Statistical diagnostics confirmed model adequacy and uncovered outliers for further investigation. Based on visibility conditions. This model is suitable for Lagos, where real-time visibility measurements especially during fog-prone early mornings can be used to assess signal loss and guide system design.

Fog consists of suspended water droplets or ice crystals, which scatter, absorb, and reflect EM waves, reducing signal power. In extreme conditions, attenuation may exceed 100 dB/km, well beyond the 20–30 dB fade margin of typical FSO links. This severely shortens transmission distances (especially in the 500 m–4 km range).

Effects Include:

- Reduced transmission range
- Increased error rates
- Decreased data throughput
- Signal fading

High-frequency systems (e.g., microwave, FSO) are particularly vulnerable. Fog can degrade capacity, induce losses, and impair reliability. Studies cite attenuation levels up to 128 dB/km in dense fogs.

Mitigation Strategies:

- Adaptive modulation and coding
- Redundant routing
- Real-time environmental adaptation

The regression analysis provides critical insights into how fog affects communication performance. Designing responsive, adaptive systems based on these parameters ensures more resilient and efficient networks, particularly in regions like Lagos with high environmental variability.

CONCLUSION

This study confirms that fog-induced attenuation in communication links is significantly influenced by environmental parameters—primarily visibility, followed by temperature and humidity. Among these, visibility proved to be the most critical factor, with signal attenuation increasing sharply when visibility dropped below one kilometer, particularly during the fog-heavy months of January and December. Regression analysis showed strong inverse relationships between these variables and attenuation at 850 nm and 1550 nm wavelengths, establishing visibility as the most reliable predictor of signal loss, consistent with prior findings (Kim & Korevaar, 2001); (Al Naboulsi, 2004)). This aligns with literature which shows that fog, composed of water droplets or ice crystals, scatters and absorbs electromagnetic waves, leading to increased signal degradation (Andrews & Phillips, 2005). The research achieved its objectives by quantifying attenuation levels at key wavelengths, analyzing the impact of meteorological parameters through multiple regression, and evaluating their implications for system reliability. Furthermore, the study contributes new insight into optimal wavelength selection for free-space optics, highlighting the relative resilience of infrared wavelengths like 1550 nm, as supported by studies in optical communication (Majumdar & Ricklin, 2008). Based on the findings, it is recommended that FSO systems prioritize infrared wavelengths due to their lower susceptibility to Mie scattering in fog (Kahn, 2002). Communication networks should also adopt adaptive modulation and coding schemes that adjust transmission based on real-time environmental data, a method known to increase link availability during adverse weather (Scott Bloom, 2003). Additionally, integrating predictive analytics with live monitoring of visibility, humidity, and temperature enhances the resilience of such systems in fog-prone areas, like Lagos, Nigeria. Such strategies are essential to achieving robust and uninterrupted communication, especially in environments where climatic variability presents significant challenges to optical link reliability.

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