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Development of an Improved Rain Attenuation Prediction Model for Wireless Communications Networks Operating AT 38GHz Millimeter Wave Frequency

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ABSTRACT

This research focused on developing an improved rain attenuation prediction model for wireless communications at 38 GHz using Adaptive Neuro-Fuzzy Inference System (ANFIS) and Artificial Neural Networks (ANN). The study utilized rainfall data from 2011 to 2021 in the Zaria metropolis, employing the ITU-R P.838-3 model to calculate specific attenuation due to rain. Key input parameters included rain intensity, signal frequency, and polarization. MATLAB 2021a was used for calculations, converting specific attenuation into an equivalent path length. The improved model demonstrated greater accuracy than the ITU-R P.838-3 model, particularly in areas with high convective rainfall. The Mean Square Error (MSE) of 0.396085688 and Root Mean Square Error (RMSE) of 0.6293533 indicated high precision in predicting rain attenuation. This model is suitable for designing reliable wireless communication systems in the study area.

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INTRODUCTION

The development of an improved rain attenuation prediction model for wireless communications networks operating at 38 GHz millimeter wave frequency is crucial due to the increasing reliance on higher frequency bands for enhanced bandwidth and communication efficiency. Rain attenuation significantly impacts the performance of telecommunication systems, particularly in the SHF and EHF ranges, where electromagnetic waves are susceptible to atmospheric conditions [6]. Recent methodologies have focused on leveraging extensive meteorological data to enhance prediction accuracy, as demonstrated by Capsoni *et al*. who proposed a comprehensive statistical model for rain horizontal structure [1-3].

Additionally, improved extrapolation techniques for rain attenuation cumulative distribution have been developed, particularly for tropical regions, which can be adapted for various geographical contexts [4]. Furthermore, the application of advanced simulation methods, such as ray tracing, has shown promise in accurately predicting millimeter-wave propagation, thereby facilitating better network design and performance [4]. This research highlights the challenges in designing stable and reliable microwave radio frequency systems, particularly due to rain-induced signal attenuation through absorption and scattering. Effective planning and analysis are essential to prevent system outages and ensure optimal performance [5, 6].

Millimeter wave (mm-Wave) communications, operating in the 30 GHz to 300 GHz range, are crucial in supporting wireless applications. Researchers have developed various models to understand and mitigate atmospheric impacts on wireless communication quality. Most studies have focused on empirical data from cellular backhaul networks, particularly at frequencies between 10 to 38 [GHz], for rainfall monitoring. However, existing rain attenuation models, such as the ITU-R model, are often site-specific. Given the unique local conditions, this research underscores the need for a realistic rain attenuation model tailored to the Zaria metropolis. The Q Band, defined by ISO as 36 to 46 GHz, lies

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between the IEEE Ka-Band (26.5–40 GHz) and V-Band (40–75 GHz), though IEEE or ITU does not recognize it. The 38 [GHz] frequency, used in this study, falls within the millimeter wave region, beyond the traditional microwave band. This frequency operates in the millimeter wave spectrum, which differs from lower-frequency microwave links. Figure 1, in the study, illustrates the electromagnetic spectrum, showing the position of these frequency bands.

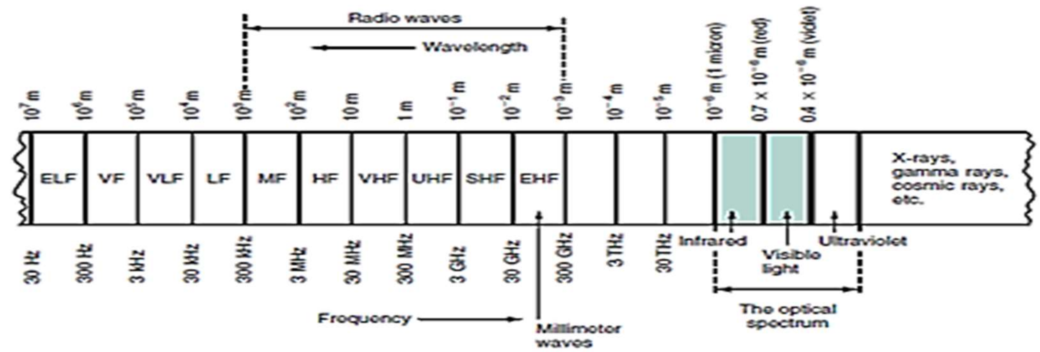

Figure 1: Electromagnetic spectrum used in electronic communications [2]

LITERATURE REVIEW

This section reviews fundamental concepts and related works on signal propagation under rain. It covers existing theories on rain-induced signal attenuation due to absorption and scattering, considering factors like rain intensity and droplet sizes and shapes. The review highlights the importance of understanding diverse rain characteristics across different geographical locations for accurate rain attenuation modeling. Such modeling is essential for designing and optimizing reliable communication systems in rain-prone regions, underscoring the need for further research to refine existing models and algorithms.

In [7], researchers proposed a rain attenuation prediction model for terrestrial links in southwest Nigeria using an adaptive artificial neural network. They used data from three Nigerian microwave connections at 23 and 38 GHz. At 23 GHz, they found that a normal distribution with an average of zero better represented the fade slope distribution compared to the ITU-R earth-to-satellite rain fade slope model. They developed a novel prediction model validated with 38 GHz data, which showed good performance across various attenuation levels. However, their study did not address the issues of spatial variability and data quality, which are crucial for the model's accuracy and reliability.

In [8], regression analysis was used to develop a rain attenuation prediction model using rain rate and percentage of exceedance as inputs. The non-linear least square regression method was employed to determine the best coefficients for the model. This proposed model's results were compared with those from ITU and ANN prediction models. The comparison showed that the proposed model outperformed the ITU and ANN models, achieving a lower sum of residual squares (SRS) and root mean square error (RMSE). The study concluded that ITU-R and ANN models were not suitable for Charbonneau and Japan, highlighting the need for a site-specific rain attenuation prediction model for the Zaria metropolis to ensure efficient communication.

[5] examined the Learning Assisted Rain Attenuation Prediction Model (LARA), categorizing it based on input parameters and conducting a comparative analysis for each supported frequency component. However, the study did not address the complexity associated with the proposed model.

[9] the researcher uses five rain attenuation models for earth-space links operating at frequencies ≥ 10 GHz in North Central Nigeria. The models considered are ITU-R P.618-9,

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Bryant, Simple attenuation, Garcia-Lopez, and Svjatogor. Rainfall data from the Centre for Atmospheric Research (CAR), Anyigba, Nigeria, with 2–4 years of 5-minute integration time, was used. The study analyzes the cumulative distribution of rain attenuation at the Ku-band for circularly polarized signals at different percentages of time of the year. Results show that the ITU-R P.618, Garcia-Lopez, and Bryant models performed optimally in the region, with attenuation values ranging from 6 to 19 dB at an exceedance time percentage of 0.01% in all stations.

METHODOLOGY

Rain Attenuation

A. Rain attenuation is a phenomenon affecting satellite and terrestrial communication systems, where transmitted signals weaken or fail due to rain in the transmission path. This occurs as rain droplets absorb or scatter electromagnetic waves, particularly at high frequencies used in these systems. The severity of attenuation increases with higher frequencies and is influenced by rainfall intensity, duration, and distance between antennas. Designers mitigate these effects using techniques like diversity reception with multiple antennas or opting for lower frequency bands less susceptible to rain attenuation. Figure 2: Workflow of rainfall prediction.

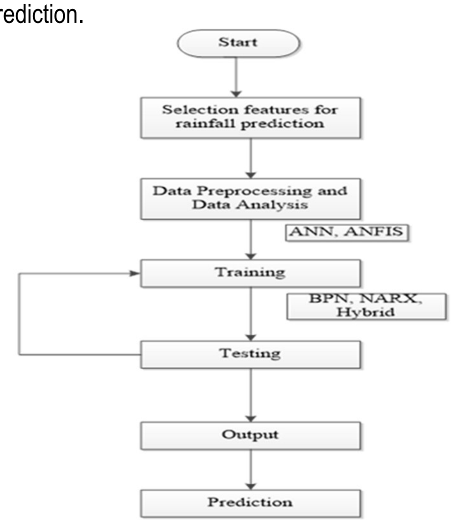

Figure 2: Workflow of Rainfall Prediction

Specific attenuation (γ)

Specific attenuation (γ) refers to the reduction in signal strength as it travels through a medium, typically expressed in decibels per kilometer (dB/km). Rain attenuation, a form of this phenomenon, quantifies the signal power decrease caused by rain compared to clear weather conditions. It occurs due to the absorption, scattering, and reflection of electromagnetic waves by rain droplets. Specific attenuation due to rain is influenced by factors like rain rate, frequency, and atmospheric conditions, and is crucial in assessing signal quality and reliability in communication systems.

Estimation of Duration for Rain Rate Exceeding Threshold Rq

The study calculates the number of hours each year that the rain rate exceeds a threshold of 10 mm/hr, indicating periods of significant rain attenuation affecting telecommunications. The calculation is based on data spanning eleven years, totaling 168 hours annually when considering the occurrence of rain rate surpassing the specified threshold. This analysis provides valuable insight into the frequency and duration of rain-induced signal degradation over the study period.

Calculation of Rain Attenuation

The rain attenuation in Zaria can be calculated using MATLAB 2021 with the formula L = rainpl(range, freq, rain rate), as shown in equation 3.1. Here, L represents the attenuation in decibels (dB), and rainpl is a MATLAB function designed for this purpose. The inputs to the function include range (distance traveled by the signal), freq (signal frequency in GHz), and rain rate (rainfall intensity in mm/hr). This approach enables accurate estimation of signal attenuation due to rain, leveraging meteorological data to enhance the reliability of communication systems in Zaria.

Description of the Parameters

The MATLAB function rainpl(range, freq, rain rate) calculates signal attenuation (L) due to rainfall using the International

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Telecommunication Union (ITU) rainfall attenuation model. It assumes the signal path is within a uniform rainfall environment where the rain rate does not vary along the path. The function considers parameters such as signal path length (range), signal frequency (freq) in the range of 1–1000 GHz, and rainfall intensity (rain rate) in mm/hr. Path elevation angle and polarization tilt angles are assumed to be zero in this model. The function provides a method to estimate how rain affects signal propagation, crucial for designing reliable communication systems in regions prone to rainfall like Zaria.

Training, Testing, and Validation for rain attenuation prediction

In the process described, a database is created from inputs and outputs for training neural network models using MATLAB (2021a). The next phase involves training the input data using the feed-forward backpropagation algorithm. MATLAB's NNTOOL is utilized for this purpose. During training, 70% of the input data is used for training the neural network model, while 30% is automatically reserved for testing and validation. The objective is to achieve acceptable error levels during testing, ensuring the model's reliability and accuracy in predicting outcomes based on the input data.

Applying Feed Forward Back Propagation Algorithm Model for Rain attenuation prediction

The study focuses on utilizing the backpropagation algorithm to achieve accuracy in training, testing, and validating input and output data specific to Zaria. Figure 3.5 illustrates the network architecture of the feed-forward backpropagation algorithm models used for predicting rainfall attenuation. This architecture is central to the study's approach, aiming to develop a reliable model for estimating how rain affects signal propagation in the Zaria region.

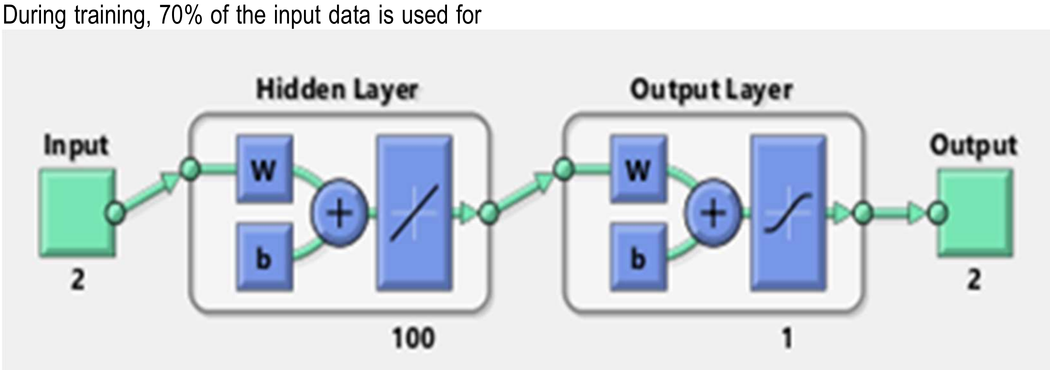

Figure 3: Feed forward back propagation network architecture of rain attenuation prediction (MATLAB, 2021a)

The study proposes a feed-forward backpropagation algorithm model for predicting rainfall attenuation, focusing on rain attenuation and frequency as inputs. The network architecture includes 100 neurons distributed across two hidden layers, with an emphasis on optimizing rain attenuation prediction. The training utilizes the Levenberg Marquardt algorithm (trainlm) known for its efficiency in refining weight and bias values dynamically. The Purelin transfer function is selected for its proven accuracy and performance, ensuring high-quality outcomes during training. Results from training, testing, and validation over 5 epochs are analyzed for accuracy, as shown in Figure 4.

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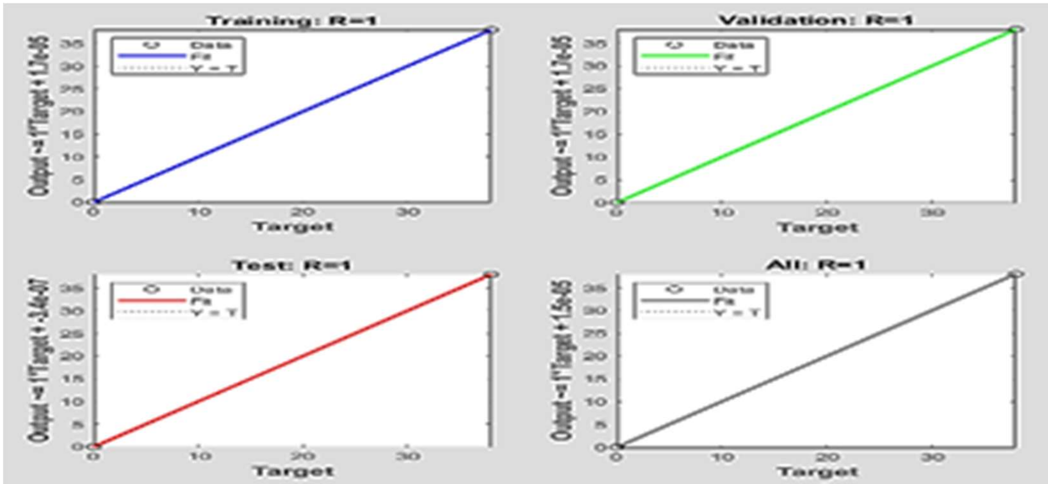

Figure 4: Snapshot of regression using NNTOOL (MATLAB, 2021a)

The training, testing, and validation phases of the proposed model achieved perfect accuracy scores of 1 out of 1. This indicates precise and accurate results across all stages of evaluating the model's performance. The study demonstrates high reliability in predicting rain attenuation using the feed-forward backpropagation algorithm, leveraging efficient training methodologies and optimal model architecture.

RESULTS AND DISCUSSION

The simulation model was created using MATLAB (2021a) and Microsoft Excel (2019) programming environments. Chapter three details the methodologies employed to achieve the research objectives. The simulation results, based on these methodologies, are discussed and presented comprehensively, showcasing the effectiveness and outcomes of the developed model in predicting rain attenuation.

Rain attenuation distributions (2011-2021)

Daily trends in rain attenuation for Zaria were plotted using Excel. The dataset, sourced from the primary table in Appendix A, includes chronological dates in the "Date" column and corresponding rain attenuation values in the "Rain Attenuation" column. Figure 5 illustrates the plot depicting the daily distribution of rain attenuation over time in Zaria. This visualization provides insights into how rain attenuation fluctuates daily in the study area.

Monthly rain attenuation data from 2011 to 2021 for Zaria was analyzed using MATLAB.

The analysis aimed to identify trends and variations in rain attenuation over this period, leveraging meteorological data for accurate calculations. The results highlight annual cycles of rain attenuation, providing insights that can be effectively utilized for predictive purposes.

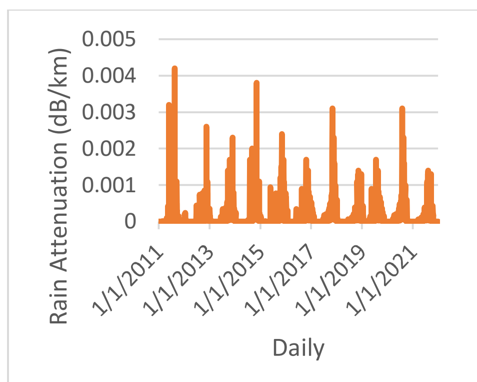

Figure 5: Daily trends in the distribution of Rain attenuation for Zaria (Microsoft Excel. 2019)

This analysis serves to understand how rain attenuation fluctuates every month over the eleven years, crucial for designing reliable

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communication systems and mitigating signal degradation in Zaria.

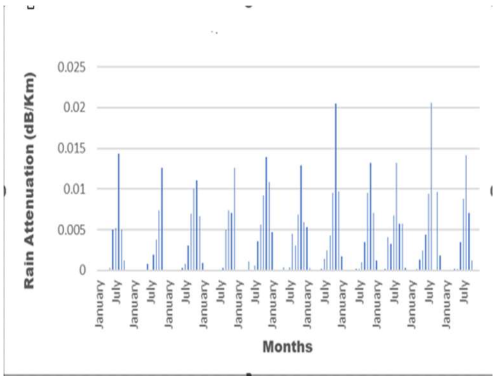

Figure 6: Monthly trends in the Distribution of Rain attenuation for Zaria (Microsoft Excel. 2019)

The study investigates monthly rain attenuation trends in Zaria using an eleven-year dataset, focusing on variations and seasonal patterns in attenuation values. Figure 6 visually presents these trends, highlighting monthly fluctuations in rain attenuation dynamics. Additionally, Figure 7. depicts the annual distribution of rain attenuation from 2011 to 2021, showing varying yearly cycles while maintaining an overall consistent pattern in attenuation levels over time.

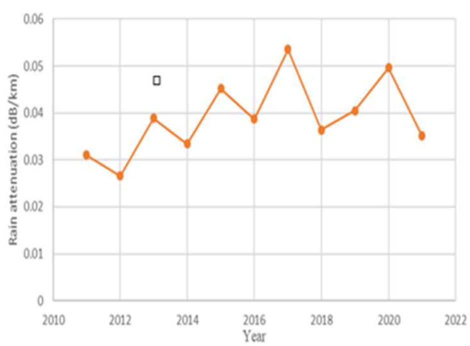

Figure 7: Yearly Trends in the Distribution of Rain Attenuation for Zaria (Microsoft Excel. 2019)

Comparison of ITU-R P. 838-3 and Measured Specific Attenuations Models

Figure 7. displays yearly rain attenuation data from 2011 to 2021 for Zaria, calculated using MATLAB with meteorological data from the Centre for Atmospheric Research (CAR). The graph illustrates trends and variations observed over this period, emphasizing annual cycles of rain attenuation that are valuable for predictive purposes.

Figure 8, shows a graph depicting the characteristics of specific attenuation obtained from a measured dataset spanning 11 years. In contrast, Figure 9, displays a graph derived from calculated values using the ITU-R P.838-3 model over the same 11-year period.

Figure 11 displays a comparison between specific attenuation values in dB/km. On the left side, there are the calibrated calculated data (using ITU R P. 838-3), while on the right side, there are the derived measured values.

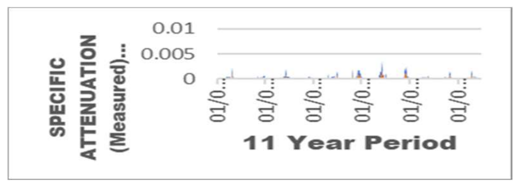

Figure 9: Measured Specific Attenuation of 11-year period (Microsoft Excel, 2019)

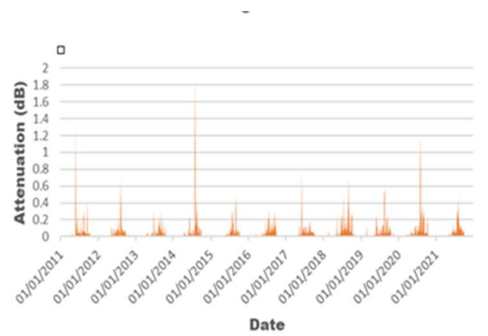

Figure 10: ITU-R P. 838-3 Specific Attenuation of 11-year period (Microsoft Excel, 2019)

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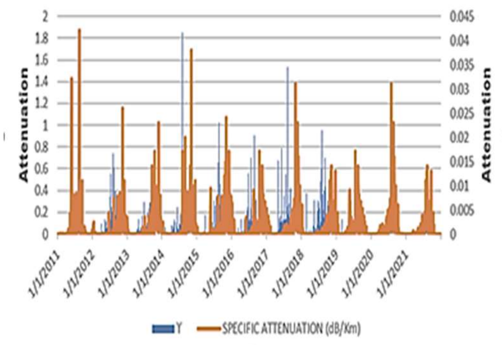

Figure 11: ITU R P. 838-3 and measured specific attenuations (Microsoft Excel, 2019)

Figure 11 visually compares calculated attenuation values obtained using the ITU-R P.838-3 method (marked in blue) with measured attenuation values (marked in brown) over 11 years. This color-coded representation clearly distinguishes between the calculated and empirical datasets, facilitating an easy comparison to assess agreement or divergence between them. The study aims to enhance rain attenuation prediction beyond the ITU-R model, focusing on optimizing wireless communication networks operating at 38 GHz in Zaria. Figures 12 and 13 illustrate the evaluation and optimization process, while Figure 4.19 presents a comparison graph of specific rain attenuation against rainfall rates based on a conservative threshold of 10 mm/hr from 2011 to 2021.

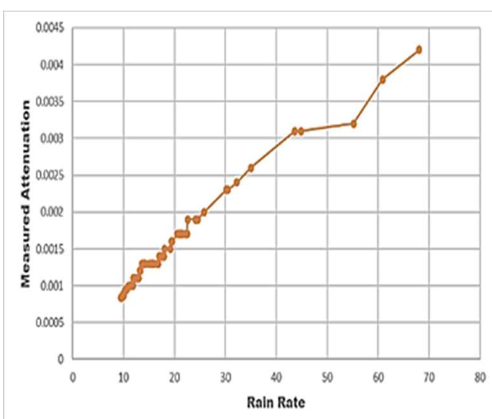

Figure 12: Measured Specific attenuation against Rain Threshold (Microsoft Excel, 2019)

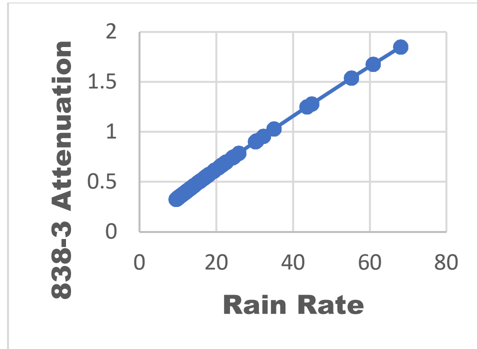

Figure 13: ITU-R P. 838-3 Specific Attenuation against Rain Threshold (Microsoft Excel, 2019)

Figure 14 presents a comprehensive comparison graph that facilitates a detailed evaluation of specific rain attenuation relative to corresponding rainfall rates. The dataset analyzed includes 84 instances spanning from 2011 to 2021, summarizing attenuation profiles based on a conservative threshold of 10 mm/hr for rainfall intensity. This comparative analysis aims to provide a robust, data-driven assessment of how rain affects attenuation over the specified period, aiding in the refinement and optimization of rain attenuation prediction models for wireless communication networks.

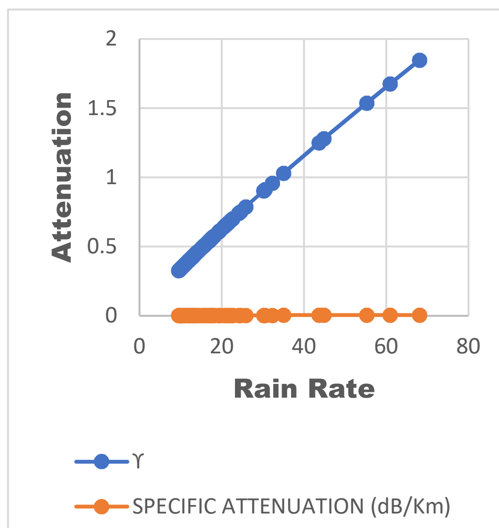

Figure 14: Comparison Graph Between Specific Attenuation and Rain Rate

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Figure 14: Comparison of ITU-R P. 838-3 and Measured Specific attenuations against Rain Threshold (Microsoft Excel, 2019)

Figure 14 visually compares specific rainn attenuation against a range of rainfall rates, offering insights into their relationship. It aids in forming informed evaluations of attenuation patterns over the studied period, using a conservative 10 mm/hr rainfall threshold. The graph highlights that measured rain attenuation performs better than calculated values, validating the research goal of enhancing predictive models for Zaria's conditions.

Comparing Measured and Predicted (ITU-R P. 838-3) attenuation results

Table 1: Comparison of Measured and Predicted results (ITU-R P. 838-3) attenuations Capacity.

Zaria Attenuation @ 38GHz	Measured Attenuation	ITU-R P. 838 Attenuation
Mean	0.001414	0.556085
Median	0.438423	0.001200
MSE	0.396085688	
RMSE	0.6293533	

CONCLUSION AND SUMMARY

Conclusion

In the past decade, Zaria experienced consistent rainfall patterns, with 2020 recording the highest rainfall of 1098 mm and 2013 the lowest at 583 mm. This data indicates nearly continuous precipitation over the years in the region.

Summary

This research provides a foundational framework for developing predictive models for rain attenuation in wireless communication networks, but further refinement is needed. Key recommendations for future work include optimizing the model for accuracy and robustness, ensuring adaptability to changing environmental and technological conditions, enhancing predictive capabilities through new data and methodologies, and contributing to the scientific community by addressing current model limitations. These steps aim to create more reliable tools for predicting rain attenuation, improving signal quality in wireless networks.

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