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RESEARCH ARTICLE

Sand and Dust Storm Attenuation Prediction Using Visibility and Humidity Measurements

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ABSTRACT Sand and dust storms present significant challenges to microwave and millimeter-wave propagation, directly impacting communication systems. Despite the existence of various theoretical and analytical models for predicting dust storm attenuation, many have overlooked the crucial factor of humidity. This study had conducted a year-long monitoring of visibility, humidity, and received signal levels for two microwave links operating at 14 GHz and 22 GHz in Khartoum, Sudan. The percentage variation in visibility during a dust storm is 95%, and the percentage variation in humidity is 78%, as the received signal level varies from −42.17 dB to −82 dB. The research unveils a notable correlation between fluctuations in humidity and the complex permittivity of sand and dust particles. Furthermore, this study proposes an empirically developed prediction model for sand and dust storm attenuation, surpassing existing models by incorporating both visibility and humidity data. In contrast to models that solely rely on measured visibility and neglect humidity, this research methodology takes into account both of these measured parameters during dust storms to predict attenuation at any desired frequency. The model's performance is validated through measurements at 14 GHz, 22 GHz, and 40 GHz, demonstrating robust agreement with the collected data. This comprehensive model provides a more accurate representation of the complex weather conditions during sand and dust storms, enhancing the readability of microwave links design by accurate prediction and mitigation of their impact on communication systems.

INDEX TERMS Sand and dust storm attenuation, micro and millimeter wave propagation, visibility and humidity, complex permittivity, terrestrial communication.

I. INTRODUCTION

Various atmospheric conditions, such as sand and dust storms, rain, fog, and haze, play a critical role in visibility limitation and are pivotal factors in evaluating the availability of micro and millimeter wave links that's requests further research in modelling attenuation for 5G/6G frequency bands, offering a valuable tool for testing different attenuation models at the network level [1], [2].

An analysis of the effects of the sand and dust storms and whether parameter variation on micro_ millimeter wave propagation, particularly in high-frequency bands, emphasizes the

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need for an effective and reliable methodology for estimating sand and dust storm attenuation, a crucial consideration in designing efficient systems [2].

A reduction in visibility corresponds to an increase in attenuation. The effect of sand and dust storms on electromagnetic wave propagation presents a complex challenge, posing difficulties in theoretical model articulation. Sand and dust storms are intricate phenomena directly influencing micro- and millimeter-wave propagation [3], [4]. Numerous theoretical, analytical, and semi-empirical models have been developed to predict attenuation resulting from these storms, based on scattering theories and Estimations of dust particle properties, encompassing factors such as shape, dielectric constants, and size [4], [5], [6]. However, in practice, none of these models has proven reliably predictive when compared with attenuation that measured for various frequencies in arid areas [3], [4], [5]. Properties of sand and dust storms and their impact on micro and millimeter-wave propagation are categorized as complex phenomena, posing challenges in theoretical disciplines. Several attenuation models were developed theoretically, analytically, and semi-empirically to assess dust storm attenuation [6], [7], [8], [9], [10], [11]. Efforts to simplify the intricacies of micro and millimeter-wave propagation in dusty environments through approximations of dust particle properties did not yield accurate forecasts when compared to attenuation measurements in arid regions [5], [12]. Numerous measurements indicate relationships between visibility, humidity, and attenuation [5], [12], [13]. Sand and dust storm characteristics, recognized as complex phenomena, present challenges in theoretical articulation due to the reported unsystematic nature of dust particles, which cannot be assumed to be spheres or ellipsoids, as some models suggest [4], [14]. On the other side, findings from environmental studies indicate that the concentration of sand and dust particles throughout storms is predominantly influenced by factors such as wind speed and relative humidity. [15]. The dielectric constant of sand and dust storm samples is based on chemical composition, frequency, and moisture content [14], [16], [17]. "Moisture content" refers to the amount of moisture in sand and dust particles, while relative humidity measures the moisture quantity in the surrounding air [18]. Several studies highlight a noticeable shift in relative humidity during storms directly altering the moisture content and dielectric constant of sand and dust storm particles. This shift significantly degrades signals due to changes in the characteristics of these particles [5], [12], [13], [19], [20].

Restricted research has explored the characteristics of dust particles, particularly focusing on conditions of low moisture content or desiccated dust particles. In a dry air environment, studies indicate minimal or zero shifts in dielectric constant components. However, a discernible shift was observed in the imaginary component of complex permittivity (loss factor), along with a noticeable increase in both moisture content and frequency [19]. Dust particle tests conducted in Khartoum, Sudan, revealed that hygroscopic water can augment the complex permittivity of dust, especially in the imaginary component. At 82% relative humidity, dust was found to absorb 5.1 percent by weight of moisture [11]. Investigations into various sizes of soil samples (sand, silt, clay) demonstrated a gradual rise in the dielectric constant corresponding to an increase in moisture content [20]. The rise in water content is depicted as relative humidity (RH) increases in untreated sand without clay. The gradual rise in water content continues until reaching 75% relative humidity [13]. A recent study proposed a model, covering 4–45 GHz, factors in excess charges and humidity, particularly addressing water vapour's role in high visibility [21]. In another study, Lasne et al. [22] and colleagues established a noteworthy connection between the permittivity of sand and dust particles and their moisture content. This correlation formed the basis for an empirical model, developed by Elsheikh [5], through the extensive study of visibility, frequency, moisture content, and imaginary component of complex permittivity of sand and dust particles, it's important to highlight that these model did not take into account the changes in moisture levels, especially when there were significant increases in humidity. While variations in sand and dust particle moisture content are difficult to measure during dust storms, humidity levels remain quantifiable [5], [12], [23].

Lastly, a research project inquiries into how sand and dust storms affect electromagnetic waves in communication networks. It introduces a statistical model based on frequency and visibility, using NASA data for the Gulf area. The study compares sandstorm attenuation with rain and gaseous attenuation, contributing insights into atmospheric conditions' impact on communication networks [24]. The impact of sand and dust storms on micro and millimeter-wave frequencies, as illustrated in Figure 1, has described the attenuation and signal degradation experienced during adverse weather conditions [25]. However, variations in the moisture content of the sand and dust storm particles are not measurable during dust storms, but humidity remains a measurable quantity. Hence, the impact of humidity on predicted attenuation is substantial, yet the forecasted values consistently fall significantly below the observed attenuation levels. Therefore, a thorough investigation of the models, with a specific emphasis on humidity, is strongly required to improve overall accuracy.

This paper makes a notable contribution by empirically formulating a prediction model for attenuation during sand and dust storms. This model is based on key factors such as visibility, humidity and frequency. This development stems from a one-year concurrent observation of fluctuations in microwave signal, correlating them with changes in visibility and humidity. Additionally, a correlation is established between humidity fluctuations and their influence on the complex permittivity of sand and dust particles. The proposed predictive model can be utilized for designing dependable microwave systems in areas where measured visibility and humidity data are available. The subsequent sections of this manuscript are delineated as follows:

Section II elucidates the experimental setup, encompassing the intricacies of data collection and measurements. In Section III, a new relation of the complex permittivity function on frequency and humidity is introduced, and attenuation prediction based on complex permittivity, humidity, frequency, and visibility is proposed. In section IV, the attenuation prediction is validated. The conclusion of this study is encapsulated in Section V. This study significantly advances our understanding of humidity impacts on signal attenuation. Future research could explore additional environmental variables and their interactions.

II. EXPERIMENTAL SETUP AND DATA COLLECTION

Metrological parameters, including visibility and humidity, were monitored in Khartoum, Sudan, from June 1, 2014, to May 31, 2015, for links operating at both 14 GHz and 22 GHz. This comprehensive monitoring period offers a detailed dataset for investigating the atmospheric conditions in Khartoum, shedding light on the intricate interplay between metrological parameters and the performance of communication links at 14 GHz and 22 GHz. The findings from this extended observation period provide valuable insights into the environmental factors influencing the reliability of wireless communication systems in the region.

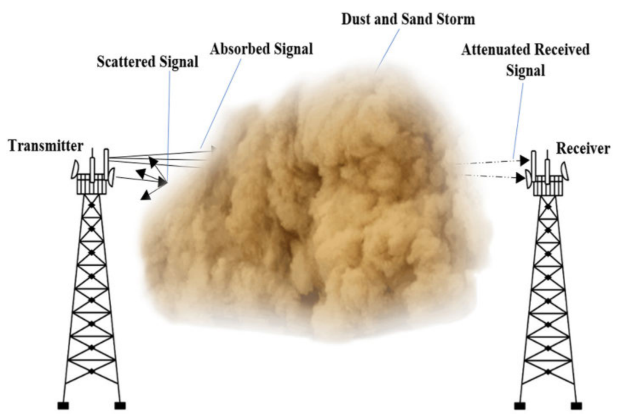

FIGURE 1. The impact of sand and dust storms on micro and millimeter-wave frequencies.

A. DATA COLLECTION

The monitored signal levels were received from two microwave links operating at 14 GHz, with path lengths of 2.6 km, and at 22 GHz, with path lengths of 2.8 km in Khartoum, Sudan, Covering the period from June 1, 2014, to May 31, 2015, as shown in Figure 2. Simultaneously, Meteorological parameters, encompassing visibility, relative humidity, temperature, wind speed, and atmospheric pressure, were systematically recorded throughout the same period, in conjunction with the monitoring of received signal levels. Rain, fog and haze are found insignificant during dust and sand storms in semi-arid area and consequently its effects on signal attenuation were neglected. Additionally, comprehensive data analysis was conducted to investigate potential correlations between the monitored signal levels and meteorological parameters.

Even though measurement was conducted for one year period, but good number of dust storm events and corresponding signal attenuation will develop a reliable attenuation prediction model This involved methods to determine patterns and trends, allowing for a more nuanced understanding of the impact of atmospheric conditions on microwave link performance.

B. RECEIVED SIGNAL LEVEL

The two-microwave links are positioned approximately 5 km northeast of Khartoum airport, as shown in Figure 2. The link named Shakeer–Magharba operates at 14 GHz with path lengths of 2.7 km, and the other link named Maygooma–Koukou operates at 21 GHz with path lengths of 2.8 km. Both links employ 0.6m diameter antennas. In Shakeer–Magharba, the antennas are horizontally polarized, featuring a 36 dBi gain and 19 dBm Tx power. The Shakeer antenna is elevated to 18 m, while the Magharba antenna is positioned at 24 m. In Maygooma–Koukou, the antennas exhibit vertical polarization, boasting a 40.50 dBi gain and 11.5 dBm Tx power. The Maygooma antenna is situated at a height of 17 m, and the Koukou antenna is located at 24 m [4], [5], [12]. The elevated antenna positions in both Shakeer–Magharba and Maygooma–Koukou links contribute to improved line-of-sight communication, minimizing potential obstacles. This strategic placement, coupled with the specified polarization and high gain, enhances the overall reliability and performance of these microwave links in the communication network around Khartoum airport.

C. METEOROLOGICAL PARAMETERS

Meteorological data is concurrently gathered from an Automatic Weather Station positioned at Khartoum International Airport, the station, equipped with sensors, monitors temperature (T), relative humidity (RH), wind speed, and wind direction. Meteorological parameters, including visibility, relative humidity, temperature, wind speed, and atmospheric pressure, were documented throughout the same period alongside the received signal levels. For every occurrence of a dust storm event, fluctuations in received signal levels were isolated, and over the course of a year, attenuation was estimated across all dust storm occurrences [5], [12], [26]. Visibility assessment utilized the Vaisala Transmissometer model LT31, encompassing an optical range spanning 10 to 10,000 m. Measurements occurred with a 1-minute integration period, maintaining an accuracy level of $\pm 3\%$ [4], [5], [12]. This comprehensive meteorological dataset, synchronized with received signal levels, facilitates a detailed analysis of the impact of dust storms on signal attenuation. The integration of Vaisala Transmissometer model LT31 for visibility assessment ensures precise measurements within an extensive optical range, providing valuable insights into the atmospheric conditions during dust storm events and their influence on signal propagation over time. Additionally, the dataset includes parameters such as humidity and temperature, further enriching the analysis. These factors together enable a holistic understanding of signal behavior under adverse weather conditions.

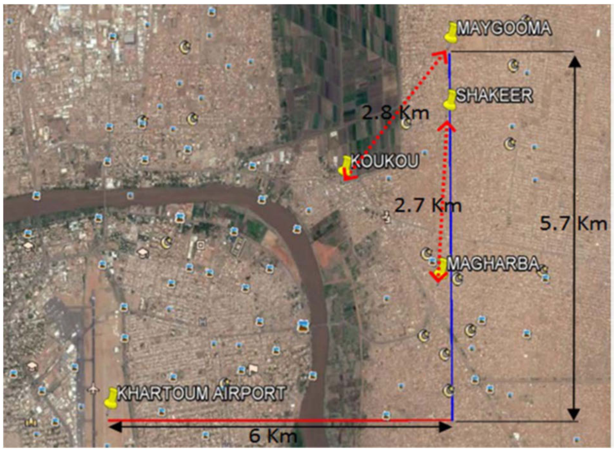

FIGURE 2. Locations of microwaves links and weather station.

D. MEASUREMENTS AND ANALYSIS

On September 27, 2014, a severe dust storm hit Khartoum. A series of dust storms followed each with different impacts on visibility, humidity, and the Received Signal Level (RSL). Each storm displayed multiple peaks, causing disruptions in communication. While part of storms showed no change in RSL despite decreased visibility, others showed simultaneous degradation in RSL and visibility. The events resembled slow-moving turbulent occurrences, affecting weather stations and communication links independently. Despite fluctuations, visibility generally returned to normal levels after each storm as depicted in Figures 3 and 4. A notable deterioration in the received signal was observed, accompanied by a substantial and remarkable elevation in relative humidity during the sand and dust storm, as illustrated in Figure 3. The alterations in humidity displayed an opposing trend to variations in signal strength and visibility, as indicated in Figure 4. Specifically, humidity levels increased while the other two parameters decreased. This observed increase in humidity was a consistent phenomenon across nearly all events in a one-year measurement period. Despite the acknowledged impact of visibility variations on prediction models, as highlighted in the literature [12], the significant rise in relative humidity during these storms has neither been acknowledged nor accounted for by existing models. The sudden surge in relative humidity has the potential to induce a notable rise in moisture content, consequently leading to substantial alterations in the characteristics of dust particles. Given that this phenomenon has been overlooked by mathematical and analytical models [6], [7], [8], [9], [10], [11], incorporating the relative humidity parameter into the prediction model of sand and dust storm attenuation becomes imperative. This inclusion allows for more accurate and realistic modeling, ultimately improving the reliability of signal attenuation predictions. Future studies should also consider the combined effects of other meteorological variables to enhance the robustness of these models.

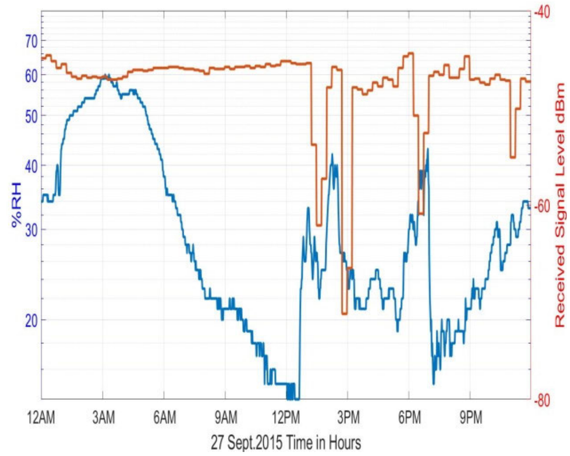

FIGURE 3. Variations in relative humidity and received signal levels over time through the occurrence of sand and dust storm at 22 GHz.

Cumulative distribution functions were calculated for observed visibility and humidity in over 20 sand and dust storm events throughout the one-year monitoring period. The results are depicted in Figures 5 and 6, respectively. As visibility and relative humidity were calculated within the same period, a direct correlation exists between relative humidity and visibility under equal probability. Consequently, relative humidity is represented as a function of visibility, as illustrated in Figure 7. These figures provide valuable insights into the relationship between visibility and humidity during dust storm events. The correlation depicted in Figure 7 offers a quantitative representation of how changes in humidity levels correspond to variations in visibility. This analysis enhances our understanding of the atmospheric conditions associated with dust storms, contributing to more informed assessments and potential mitigation strategies.

In Figure 7, a notable rise in humidity is evident during sand and dust storms, particularly at low visibility levels. A pronounced surge in humidity is observed with visibility drops up to 700 m and below 300 m. While variations in visibility have been directly incorporated into all prediction models, the influence of humidity has been overlooked by these models [5], [12], [27]. The substantial increase in relative humidity during storms, as illustrated in Figure 6, contributes to moisture absorption by dust particles, potentially altering their electrical characteristics. This overlooked impact of humidity on dust particle behavior underscores the importance of considering both visibility and humidity in comprehensive predictive models for dust storms. The distinct shifts in electrical characteristics due to increased moisture content in dust particles may have implications for atmospheric phenomena and environmental monitoring systems. Integrating these factors into predictive models enhances their accuracy and provides a more holistic understanding of the complex dynamics associated with dust storm events.

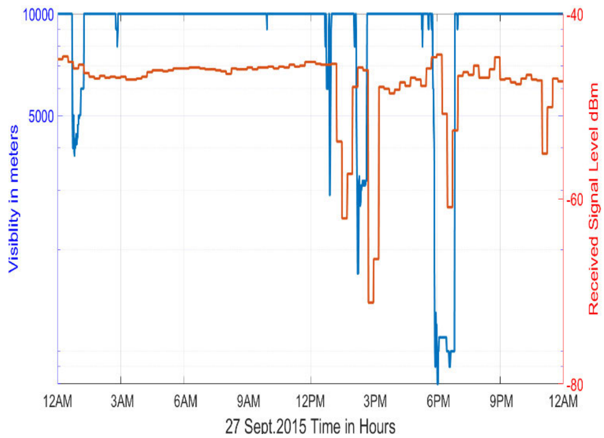

FIGURE 4. Variation in the received signal level in terms of visibility during the occurrence of sand and dust storm at 22 GHz.

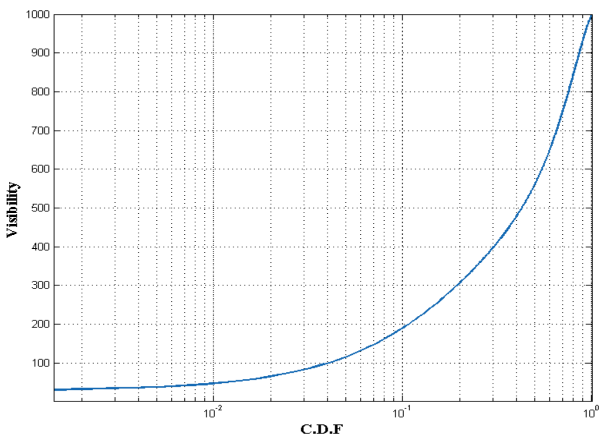

FIGURE 5. Cumulative distribution function depicting measured visibility throughout the entire duration of sand and dust storms occurrence.

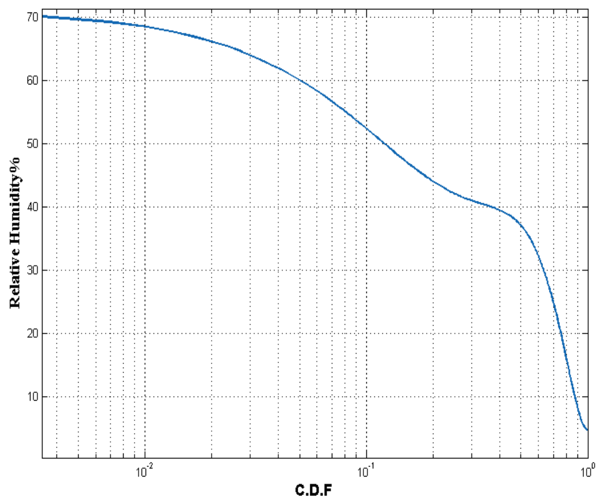

FIGURE 6. Cumulative distribution function depicting measured relative humidity throughout the entire duration of sand and dust storms occurrence.

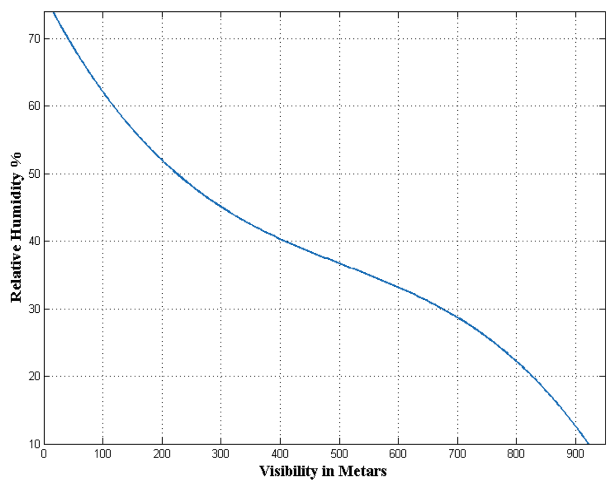

FIGURE 7. Recorded relationship between measured relative humidity and corresponding visibility throughout a one-year monitoring period of sand and dust storm events.

III. PROPOSED SAND AND DUST STORM ATTENUATION PREDICTION

The earlier research demonstrated that while the real component of the dielectric constant showed no significant relationship with frequency at moisture levels. However, the imaginary component exhibited a notable correlation within the 1–20 GHz range. Regression analysis highlights that attenuation is influenced by visibility and the imaginary component of the dielectric constant. Based on previous works and observation the equation (1) was proposed by [5]. Accordingly, an empirical prediction model for attenuation is expressed and proposed as follows:

$$\alpha \approx f\ (F, RH,\ V) \tag{1}$$

where,

α: Denotes the expected attenuation in decibels per kilometer (dB/km)

F: Denotes the measured frequency in Gigahertz (GHz)

RH: Denotes the percentage of measured relative Humidity.

V: Denotes the operating visibility in kilometers (Km).

Examinations of sand and dust samples have unveiled a robust correlation between relative humidity and moisture content [24]. Moreover, the component related to the imaginary part of the complex permittivity of sand and dust storm particles. (ε'') exhibits frequency-dependent variations under changes in moisture content levels. Consequently, the signal loss can be collectively attributed to these factors. The relationship in equation (1), between frequency, relative humidity, and frequency can be rewrite as follows:

$$\alpha = f_1 (RH, F) f_2 (V) \tag{2}$$

where,

$f_1(RH, F)$: This is the combined impact of frequency and Relative humidity on attenuation.

$f_2(V)$: This represents the influence of visibility on attenuation.

A. PREDICTION OF f1(RH, F)

Recent observations in Sudan involved the analysis of dust particle morphology using a field emission scanning electron microscope (Jeol JSM_6700F). The examination unveiled the irregular geometry of dust particles, highlighting their lack of a distinct shape. This suggests that dust particles are challenging to classify, as they exhibit irregular shapes that do not conform to traditional geometries such as spheres or ellipsoids, as illustrated in Figure 8 [14]. Moreover, the complex permittivity of sand and dust undergoes variations in response to both frequency and moisture content [5].

A thorough analysis of the data emphasizes that the shape, size, and variability of dielectric constants in dust particles, influenced by moisture content, play crucial roles in the underestimation of attenuation predictions. Across all measurements, a consistent pattern emerged, revealing a continual increase in humidity during dust storms. This pattern implies a corresponding amplification in the effects of humidity on the moisture content within dust particles during these events, ultimately influencing their electrical characteristics and contributing to heightened attenuation compared to dry conditions.

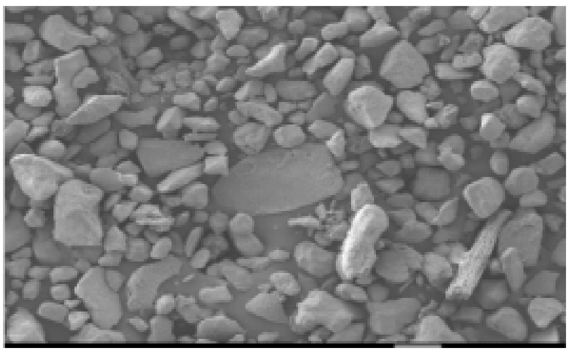

FIGURE 8. **The morphology of the dust samples under 100μm magnification.**

These findings underscore the complexity of dust particle behavior, challenging conventional modeling assumptions and highlighting the need for nuanced considerations in attenuation predictions. The consistent increase in humidity during dust storms suggests a pivotal role for moisture content, shedding light on the intricate relationship between environmental conditions, particle characteristics, and electromagnetic wave interactions in the studied region.

A previous study in [18] demonstrated a simultaneous increase in sand gravimetric moisture content as ambient humidity rises. Equation (1) facilitates the conversion from gravimetric moisture content (M_G) to volumetric moisture content (M_V), allowing for a direct transformation between these measures [29]. These findings are utilized to construct Table 1. This transformation is necessary because the relationship between frequency and the imaginary part of sand permittivity is with volumetric moisture content, as expressed in [5] and [22].

Understanding the correlation between gravimetric moisture content and ambient relative humidity provides valuable insights into the environmental dynamics influencing sand properties. The straightforward conversion to volumetric moisture content enhances the applicability of the data, contributing to a comprehensive analysis of moisture-related effects on sand's electrical characteristics in the studied context.

$$m_V = m_G \, x \, \frac{\rho_{sand}}{\rho_{WATER}} \tag{3}$$

where,

m_V = Volumetric moisture content

m_G = Gravimetric moisture content

$\rho_{sand} = 1.5$; Bulk Density of Sand

$\rho_{water} = 1$

TABLE 1. **Volumetric moisture content in sand samples across varied relative humidity levels.**

RH%	m_V
24	0.1
27	0.2
32	0.3
40	0.4
80	0.5
86	0.6

Using the findings from table 1, the moisture content is substituted into the term of relative humidity in the relationship illustrated in [5] and [22] between the imaginary part and both frequency and volumetric moisture content (M_V). This leads to a new relationship between the imaginary part and both frequency and relative humidity, as depicted in Figure 9 as a continuous line. A curve-fitting tool was utilized to establish a logarithmic relation between the imaginary part and both frequency and relative humidity, as shown in Equation (4). This relationship is visualized in Figure 9 as a discrete line. The insights gained from this analysis contribute to a nuanced understanding of how humidity influences the electrical characteristics of sand, crucial for accurate modeling in various frequency domains.

$$\varepsilon'' = C * RH * ln(F) \tag{4}$$

where,

ε'': Imaginary part of Complex Permittivity of sand.

C: is a constant utilized to transform the values of the imaginary component of sand, which varies according to the level of relative humidity.

Through regression analysis, the coefficient "C" for each humidity level enables the representation and symbolization of the term C*RH, as indicated in Equation 5.

$$\text{Ӊ} = 0.00010141(RH)^3 - 0.01716\,(RH)^2 + 0.962\,(RH) - 14.4 \quad (5)$$

Hence, the correlation involving the imaginary component of the complex permittivity of sand and dust storm particles can be expressed as follows:

$$f_1\,(F,\ RH) = f\left(\varepsilon''\right) \quad (6)$$

$$f_1\,(F,\ RH) = \text{Ӊ}\,ln(F) \quad (7)$$

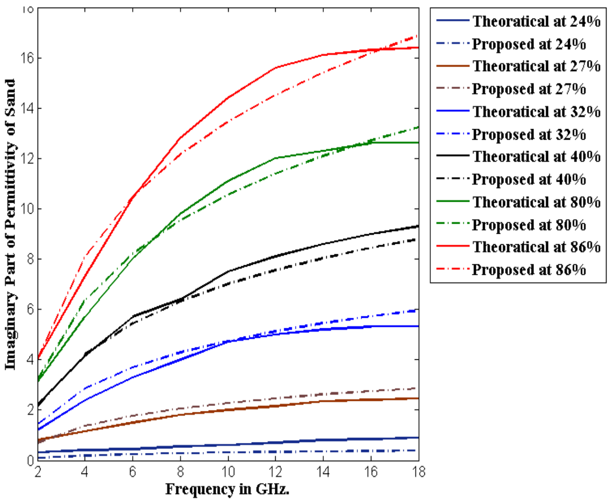

FIGURE 9. Exploring the relationship between relative humidity and the frequency-dependent imaginary component of sand's permittivity.

Therefore, the attenuation can be formulated as:

$$\alpha \;=\; \text{Ӊ}\,ln(F)f_2\,(\mathrm{V}) \quad (8)$$

B. PREDICTION OF f2(V)

The measurements unequivocally demonstrate that attenuation is influenced by relative humidity, visibility, and frequency in gigahertz, as detailed in Section II. The impact of visibility on attenuation becomes apparent through the observed correlation between measured attenuation and visibility at 14 and 22 GHz frequencies, as depicted in Figures 8 and 9. Consequently, a proposed function, $f_2(V)$ can be derived:

$$f_2\,(\mathrm{V}) \;=\; k\mathrm{V}^n \quad (9)$$

The regression coefficients, denoted as k and n, are proposed based on the frequency of the propagating wave. Consequently, the proposed attenuation prediction in equation (2) can be expressed as follows:

$$\alpha = f_1\,(F, RH)\,f_2\,(\mathrm{V}) = \text{Ӊ}ln(F)\,k\mathrm{V}^n \quad (10)$$

Following this, the coefficients 'k' and 'n' for the function $f_2(V)$ can be established through.

$$k\mathrm{V}^n = \frac{\alpha}{\text{Ӊ}\,ln(F)} \quad (11)$$

Applying equation (11) in a regression analysis involving measured attenuation (α) and observed (V, RH) at 14 and 22 GHz, statistically derived coefficients (k and n) are presented in table 2. The constancy of the imaginary part of the complex permittivity values within the 10 GHz to 20 GHz range, as evidenced in Figure 9, enables the utilization of regression coefficients (k and n) derived from 14 GHz attenuation measurements across the entire 10-20 GHz spectrum with minimal error.

The consistent behavior observed in this interval suggests that, for the frequency range of 20-40 GHz, slight variations in the values of the imaginary part of the complex permittivity can be reasonably assumed through extrapolation. Consequently, the regression coefficients (k and n) derived from 22 GHz attenuation measurements can be extended to encompass the frequency range of 20-40 GHz. This broadens the applicability of the regression coefficients (k and n).

As generalized values in Equation 12. This approach streamlines the application of regression coefficients, providing a practical and efficient means to generalize complex permittivity values across a broader frequency spectrum. By leveraging the observed consistency and extrapolating trends, the derived coefficients offer a reliable basis for predicting attenuation in the extended frequency range, contributing to the model's adaptability and robustness.

TABLE 2. The constant values '*k*' and '*n*' at 22 and 14 GHz.

Constants	22GHz	14 GHz
k	0.06513	0.07595
n	-1.125	-0.8837

Therefore, the empirically developed specific attenuation model can be formulated as follows:

$$\alpha \;=\; k\mathrm{V}^n\text{Ӊ}ln\,(F)\ \mathrm{dB/Km} \quad (12)$$

In the frequency range spanning from 10 GHz to 20 GHz., the constants are assigned as follows: $k = 0.07595$ and $n = -0.8837$. In the range from 20 GHz to 40 GHz, Ӊcan be determined based on the measured relative humidity (RH)using equation (5).

IV. VALIDATION OF THE PROPOSED ATTENUATION PREDICTION

This study extends the work of Elfatih's [5], developing upon their research that did not account for the variability of moisture content in relation to relative humidity during sand and dust storms. This research utilizes investigating the same dataset, to develop a prediction model where relative humidity is considered as input parameter and validation is conducted initially against Elfatih's [5] model and subsequently against other existing models.

The study encompassed an empirical evaluation of attenuation at frequencies of 14 and 22 GHz, with a comparison of the obtained values against those predicted by Elfatih's proposed model [5], [23], as illustrated in Figures 10, 11 and 12. Furthermore, the empirical model underwent validation against measurements conducted in Riyadh, Saudi Arabia, at 40 GHz, covering a 14 km microwave link, as detailed in [5]. The results, depicted in Figures 10, 11 and Figure 12, reveal a noteworthy agreement between the predictions of the empirical prediction and the empirically measured attenuation. The suggested model exhibits outstanding agreement across the three measurements, displaying a minor underestimation specifically at elevated visibility levels.

The data can also be analyzed to evaluate the performance of the proposed prediction and theoretical models (Elfatih, Goldhrish, Sharif, and Dong) at different frequencies (14 GHz, 22 GHz, and 40 GHz) by using ITU-R P.311-14 method [30].

So

For each percentage of time the factor S_i is calculated

$$S_i = \frac{A_P}{A_M} \tag{13}$$

where

A_P Is the predicted attenuation

A_M Is the measured attenuation

The test variable (Q_i) for each prediction method and frequency using equ (14) and (15) is calculated:

$$Q_i = ln(S_i\left(\frac{A_M}{10}\right)^{0.2}) \quad \text{When } A_M \text{is } < 10 \text{ dB} \tag{14}$$

$$Q_i = lnS_i \quad \text{When } A_M \text{is } > 10 \text{ dB} \tag{15}$$

the mean (μ_Q), standard deviation (σ_Q), and root mean square (ρ_Q) of the (Q_i) values is computed for each prediction method and frequency. The statistical parameters interpreted to assess the accuracy and reliability of each prediction method at different frequencies. The root mean square (ρ_Q) provides an overall measure of prediction performance, considering both mean and standard deviation.

So

$$\rho_Q = \left(\mu_Q{}^2 + b_Q{}^2\right)^{0.5} \tag{16}$$

By following this approach, we can systematically analyze the provided data and draw scientifically informed conclusions about the performance of different dust storm attenuation prediction methods at various frequencies as shown in table 3.

The empirical prediction validation involved calculating The root mean square (ρ_Q) values against existing prediction models, achieving highly favorable results of 0.25, 0.22, and 0.52 at 14 GHz, 22 GHz, and 40 GHz, respectively. These values were also compared to those predicted by the proposed empirical prediction using equation (16), as presented in Table 3. This comprehensive validation underscores the reliability and accuracy of the proposed empirical model across different frequency ranges. The impressive alignment between the proposed empirical model and measured attenuation, even across varying frequencies, highlights its robust predictive capabilities. The low root mean square (ρ_Q) values further affirm the model's accuracy, offering a promising tool for predicting attenuation in microwave communication systems under diverse atmospheric conditions.

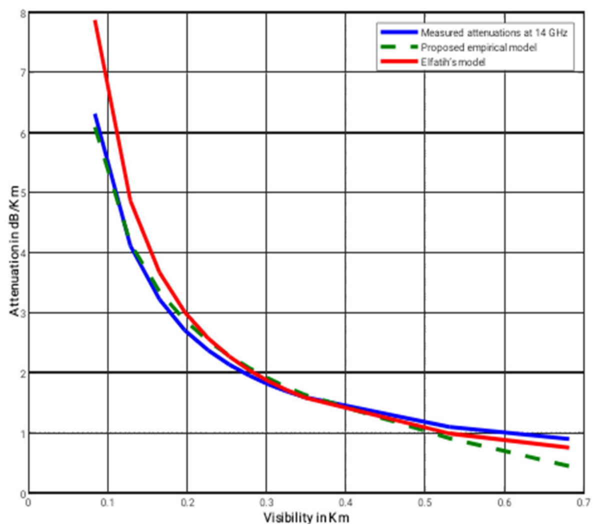

FIGURE 10. Assessment of attenuation measurements and the proposed Prediction at 14 GHz.

In the study of signal attenuation at both 14 GHz and 22 GHz frequencies, intriguing disparities have been observed between measured, predicted, and modeled attenuation values, emphasizing the need for a comprehensive investigation into the contributing factors.

At 14 GHz, where the most challenging visibility conditions of 0.08366 km were considered, careful observations indicate a measured attenuation of 6.312 dB/km, slightly higher than the predictive model's estimation of 6.093 dB/km. Elfatih's model in [5], on the other hand, records a marginally higher attenuation value of 7.82 dB/km. This variance prompts a deeper exploration into the specific environmental conditions influencing signal loss at this frequency and visibility combination.

Exploring the intricacies of signal attenuation at 14 GHz and 22 GHz opens the door to refining future communication models. Even in challenging visibility conditions of 0.08366 km, it's found that at 22 GHz, the measured attenuation of 11.42 dB/km closely aligns with predictions and a model by Elfatih's [5]. This close correspondence hints at a potential consistency in environmental factors affecting signal loss at this frequency.

The discrepancies in root mean square (ρ_Q) become notably pronounced in higher visibility ranges where

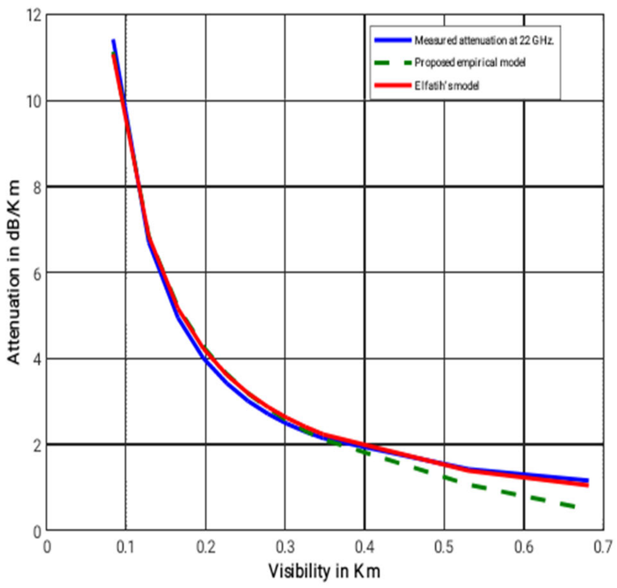

FIGURE 11. Assessment of attenuation measurements and the proposed Prediction at 22 GHz.

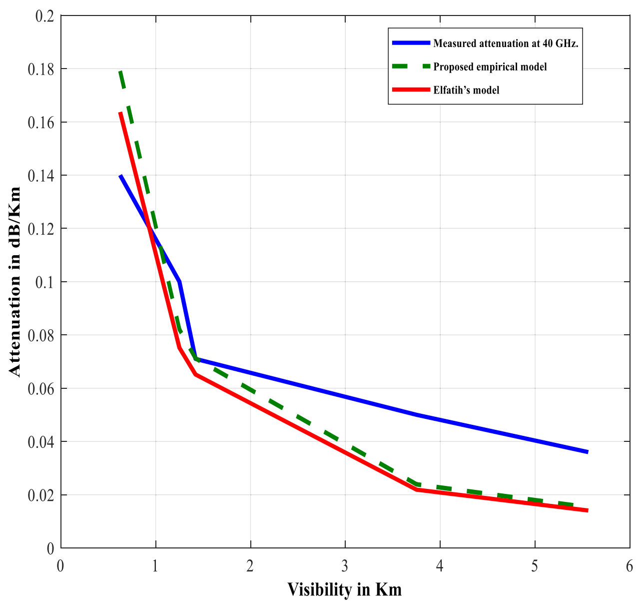

FIGURE 12. Assessment of attenuation measurements and the proposed Prediction at 40 GHz.

TABLE 3. RMSE (ρ_Q) of existing models and proposed prediction AT 14 GHz, 22 GHz, and 40 GHz.

Frequency	ρ_Q of Proposed Prediction	ρ_Q of Goldhrih Model [7]	ρ_Q of Sharif Model [9]	ρ_Q of Elfatih. Model [5]	ρ_Q of Dong Model [8]
14 GHz	0.25	6.005	5.15	0.26	6.84
22 GHz	0.22	5.99	4.49	0.17	6.73
40 GHz	0.52	2.59	0.97	0.55	3.23

attenuation is minimal. This suggests the model's exceptional performance in scenarios marked by low attenuation, particularly at 14 GHz and 22 GHz. The convergence of predictive accuracy at 40 GHz may hint at certain conditions fostering equal performance for both models.

Investigating into atmospheric conditions and interference sources is essential for a comprehensive understanding. The significance of this examination becomes apparent when considering the dual-frequency analysis. The observed and modeled values not only align but also showcase the effectiveness of the proposed prediction model. The model demonstrates exceptional performance at 14 GHz and 22 GHz, particularly in scenarios with low attenuation. The effective alignment of observed and modeled values highlights the robustness of the prediction model, especially in dual-frequency analysis.

To gain deeper insights into these distinctions, further exploration of the underlying mechanisms, such as the prediction sensitivity to attenuation levels, is crucial for understanding the predictive capabilities and limitations in diverse environmental conditions. The development of an enhanced model aims to improve the accuracy of dust storm attenuation predictions by reassessing models with a focus on humidity, crucial for better understanding the observed attenuation levels despite challenges in measuring sand and dust particle moisture content.

V. CONCLUSION

In a comprehensive study conducted in Khartoum, Sudan, visibility and humidity fluctuations were closely monitored over the course of a year, while changes in received signal levels at 14 GHz and 22 GHz frequencies were concurrently tracked. The aim was to investigate the relationship between humidity variations and their impact on the complex permittivity of sand and dust particles. An empirical prediction model for dust storm attenuation in dB/km was developed based on observed visibility and humidity data during dust storms. This model distinguishes itself from existing ones by considering both measured visibility and humidity influence. To validate the model, measurements were conducted at frequencies of 14 GHz, 22 GHz, and 40 GHz, resulting in strong agreement with root mean square error (ρ_Q) values of 0.25, 0.22, and 0.52, respectively. The model spans a broad frequency spectrum (10-40 GHz) and accommodates diverse humidity levels, from arid to humid conditions. Incorporating humidity data offers a nuanced understanding of its role in dust storm attenuation, providing a comprehensive tool for frequency specific predictions and accurate assessments in dynamic atmospheric conditions.

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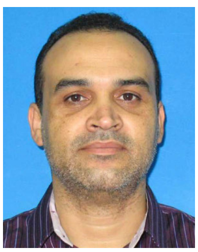

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