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RESEARCH ARTICLE

AI-Based Investigation and Mitigation of Rain Effect on Channel Performance With Aid of a Novel 3D Slot Array Antenna Design for High Throughput Satellite System

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ABSTRACT Rain attenuation poses a significant challenge for high-throughput communication systems. In response, this paper introduces an artificial intelligence (AI) model designed for predicting and mitigating rain-induced impairments in high-throughput satellite (HTS) to land channels. The model is based on three AI algorithms developed using 3D antenna design to characterize, analyze, and mitigate rain-induced attenuation, optimizing channel quality specifically in the United Arab Emirates (UAE). The study evaluates various parameters, including rain-specific attenuation, effective slant path through rain, rain-induced attenuation, signal carrier-to-noise ratio, and symbol error rate, for five conventional modulation schemes: Quadrature Phase-Shift Keying (QPSK), 8-Phase Shift Keying (8-PSK), 16-Quadrature Amplitude Modulation (16-QAM), 32-QAM, and 64-QAM. Additionally, the paper introduces a new database detailing rain-induced attenuation in HTS channels in the UAE at different frequencies using measured rainfall intensities. The paper concludes by proposing a smart antenna design with a frequency diversity technique for fade mitigation. Results indicate that rain-induced attenuation varies significantly based on rainfall rate and frequency. Specifically, at 25 GHz and a rainfall rate of 100 mm/h, the rain-induced attenuation can reach as high as 15 dB, resulting in a significant decline in signal quality and link performance. The

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proposed AI model demonstrates the ability to intelligently predict rain-induced attenuation and channel quality for various rainfall rates and frequencies. This information can be valuable for optimizing satellite link design and operation, ultimately enhancing the reliability and quality of satellite communications. The proposed two-slot smart antenna design utilizes frequency diversity to effectively mitigate rain attenuation, contributing to the overall improvement of link reliability and quality.

INDEX TERMS Rain-induced attenuation, high throughput satellite (HTS), satellite communications, artificial intelligence (AI), UAE.

I. INTRODUCTION

Modern satellite communication systems have sparked considerable interest in High Throughput Satellite (HTS) systems. These systems have become prominent for their ability to deliver efficient multimedia and broadband services at increased data rates, positioning them as focal points for the next generations of communication systems [1], [2], [3]. The demand for such HTS services has driven the need for more available bandwidth and higher data rates, leading to higher transmission frequencies [4]. Consequently, it has become imperative to characterize and model HTS channels at high frequencies to develop effective adaptive transmission models and mitigation techniques as solutions for channel impairments [4], [5]. To effectively meet user demands, it is crucial for these systems to operate at frequencies above 17 GHz [2], [3], [6].

Recent global advancements in satellite communication technologies have fueled a growing demand for advanced multimedia and broadband services provided by High Throughput Satellites (HTS) [7]. However, a major hurdle faced by HTS systems is the impact of rain-induced impairments on signal quality and link availability between HTS and terrestrial locations, especially at high frequencies [1], [8]. Raindrops act as obstacles, absorbing and scattering signal power, resulting in a degradation of signal quality as electromagnetic waves traverse through space [8], [9]. This degradation becomes more pronounced as transmission frequencies exceed 10 GHz, intensifying with higher transmission frequencies [9], [10].

To address this challenge, AI-based models offer a solution by efficiently predicting and mitigating rain attenuation in both satellite and terrestrial communication networks [11]. While widely accepted models for predicting rain attenuation have been established based on extensive observations and monitoring over the years, these models rely on information related to rainfall rates. This information can be sourced from rainfall measurement devices or predicted rainfall maps based on specific studies [12], [13]. However, it's important to note that models depending on predicted rainfall values may not always accurately forecast the performance of rain attenuation [8], [14], [15], [16], [17], [18], [19].

The accuracy of rain induced attenuation prediction models depends on the accuracy of the rainfall rate data used. Local rainfall rate measurements are preferred, especially with an integration time of at least 1-minute [15], [18], [20]. The ITU recommends using rain rate data for rain attenuation prediction [19], [20], [21], [22], but this data can be difficult to obtain. Therefore, researchers are developing new prediction models with the use of actual measured rainfall rate [19].

Rain events, constituting only a small fraction of the year, typically occur less than 5% of the time. The International Telecommunication Union Radiocommunication Sector (ITU-R) has adopted this percentage as a starting point for their model. However, to accurately characterize rainy conditions globally, it is crucial to consider a percentage of less than 1% of the time in the year, as this period encompasses the rainfall that significantly impacts signal attenuation [23]. Specifically, heavy rain, which poses the most significant challenge, occurs in just 0.01% of the annual timeframe, resulting in severe signal quality degradation. Therefore, the 0.01% figure becomes particularly pertinent when analyzing the effects of heavy or highly effective rain attenuation [24].

The existence of channel impairments emphasizes the need for a channel model capable of predicting rain-induced attenuation and assessing signal quality to implement Fade Mitigation Techniques (FMT). The demand for high-speed data services in both developed and developing countries, coupled with the complex atmospheric dynamics in certain regions like the United Arab Emirates (UAE), is further compounded by the absence of a reliable prediction model for rain-induced effects on High Throughput Satellite (HTS) channels. Additionally, there's a scarcity of rain attenuation and mitigation models based on artificial intelligence (AI) specifically tailored for 5G and beyond communication links [11]. This underscores the importance of developing an AI model customized for the unique conditions of the UAE. Hence, addressing this issue involves designing an antenna that covers a wide range of frequencies to effectively mitigate the effects of channel impairments at different frequencies.

The high data rate of High Throughput Satellites (HTS) necessitates a robust signal strength with minimal transmission errors. Achieving this goal involves the development of an efficient and adaptive antenna design integrated with fade mitigation techniques. However, challenges arise from heavy rain impairments that degrade the quality of the satellite signal, leading to increased transmission errors. These errors can pose serious problems in receiving accurate and reliable data.

In response to these challenges, this paper presents the first HTS-to-land smart channel prediction model in the United Arab Emirates (UAE), utilizing a 3D slot array cone antenna

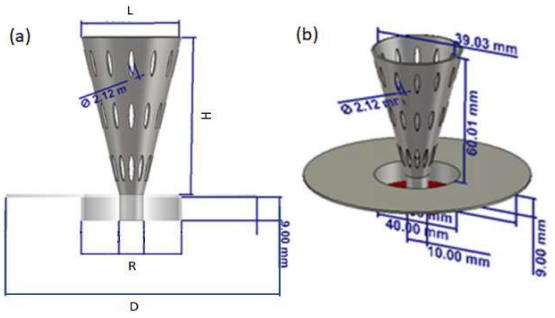

FIGURE 1. Antenna geometrical details.

TABLE 1. Dimensions of the proposed antenna element.

Parameters	Expression	Value (mm)
H	Cone height	60
L	Cone diameter	40
R	Feed aperture	40
D	Reflector diameter	100

to achieve a wideband with high gain across the entire frequency band of interest. The primary objective is to forecast the impact of rain-induced impairments and assess channel quality at the K and Ka frequency bands. Real measured rainfall data is employed with the proposed antenna, which boasts a high gain bandwidth product. Remarkably, the influence of rain on satellite communication channels in the UAE has remained largely unexplored in prior research, as far as the authors are aware. This study seeks to bridge this gap by offering valuable insights into the complexities of rain effects on HTS systems. Additionally, it proposes an innovative slot array antenna design to mitigate these effects and enhance overall channel performance.

II. ANTENNA GEOMETRICAL AND DETAILS

This section provides an explanation of the geometrical details of the antenna, with dimensions presented in millimeter scale as illustrated in Fig. 1. The proposed antenna is specifically designed to function as a high-gain end-fire antenna. In this design, a circular cross-sectional cut cone is employed to smoothly guide the wave between the microwave source and the free space impedance [25]. To further enhance performance, elliptical slots are incorporated into the cone design to reduce tangential surface waves and concentrate the main beam onto the sight bore direction [26].

Activation of the antenna involves two microwave ports positioned horizontally and vertically, with a 90° phase shift to induce circular motion along the antenna's transverse axial. To maintain directivity in the main lobe direction and increase the front-to-back ratio, a circular ground plane reflector supports the antenna [27]. The entire antenna structure measures $70 \times 100 \times 100$ mm^3 and is constructed from Aluminum in a 3D form, as depicted in Fig. 1. Additional dimensions for the proposed antenna are detailed in Table 1. For consistent microwave feeding across a wide range of frequencies, the antenna is connected through SMA type connectors.

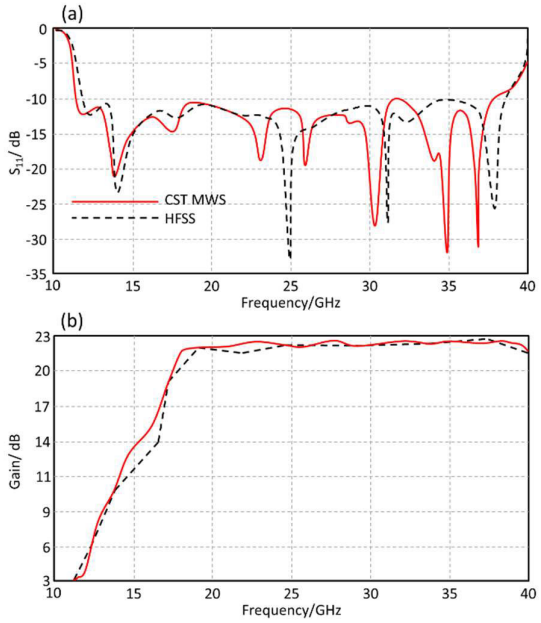

FIGURE 2. Antenna performance validation: (a) S_{11} response, and (b) gain response.

The antenna design underwent optimization through CST and HFSS 3D electromagnetic field solvers. To assess its performance, the proposed antenna's S11 and gain spectra were compared with measured results, revealing excellent agreement between simulation and measurement, as depicted in Fig. 2. Over the frequency range of 18 GHz to 40 GHz, the proposed antenna exhibits a gain of 22 dBi, accompanied by an outstanding match impedance of less than −10 dB.

Measurements indicate that the effects of rain between 18 GHz to 40 GHz can be mitigated by smoothly changing the frequency carrier during operation. This broad frequency bandwidth is achieved by incorporating an array of slots on the cone antenna, effectively suppressing surface waves, and positively impacting the impedance bandwidth of the antenna [28]. Furthermore, the directivity of the antenna is enhanced through the integration of a circular reflector at the base, positioned next to the input feed, as illustrated in Fig. 1. This reflector significantly suppresses side lobes, contributing to an overall improvement in antenna performance [29].

The proposed antenna exhibits an impressive gain bandwidth product, primarily attributed to the tangential traveling wave phenomena [30]. The axial-ratio (AR) of the antenna is illustrated in Fig. 3(a). Specifically, the AR of the proposed antenna measures approximately 3 dB at both 20 GHz and 30 GHz, which are the frequency bands of interest. Fig. 3(b) displays the radiation patterns of the antenna at 20 GHz and 30 GHz in both the E-plane and H-plane. Notably, the antenna exhibits an end-fire radiation pattern, a characteristic attributed to the effects of the antenna reflector, which contributes to achieving high normalization in the E-plane [31].

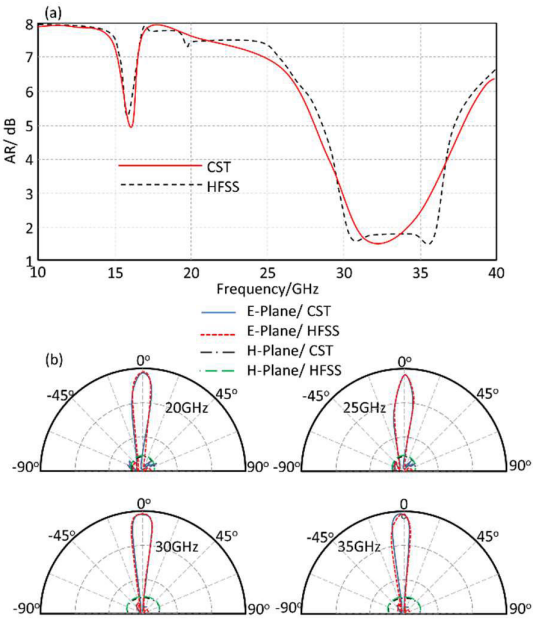

FIGURE 3. Antenna radiation properties: (a) AR, and (b) radiation patterns at 20 GHz, 31 GHz, 20 GHz, and 30 GHz.

III. EXPERIMENTAL VALIDATION AND DISCUSSION

The proposed antenna was manufactured using 3D printing technology, employing PLA (Polylactic Acid) material for its convenience and cost-effectiveness [28]. Specifically, the 3D printing technology utilized was based on Fused Deposition Modeling (FDM), known for its excellent printing precision [29]. This FDM technology operates by "slicing" the 3D model into thin horizontal layers, which are then printed on top of each other to construct the entire structure. This process generates a G-code file containing instructions for the printer. Subsequently, these G-code instructions are executed to systematically build the object layer by layer along the x, y, and z axes, with the filament being extruded through a heated nozzle onto the print bed.

The fabricated antenna was then coated with a conductive aluminum layer. To ensure a proper power match, it was fed through an SMA port. The antenna's radiation characteristics were measured within an RF anechoic chamber, as illustrated in Fig. 4, using a standard measurement setup. Notably, the reflector part of the antenna was connected to the SMA ground plane.

A comparative analysis of the proposed antenna's characteristics against other recently published works is presented in Table 2. The results reveal that the proposed antenna exhibits an outstanding gain bandwidth product when compared to findings in the existing literature, all within a sufficiently miniaturized size.

Millimeter waves find diverse applications, such as wireless communication, detection, and remote sensing [32]. However, signals operating in the millimeter wave range are significantly attenuated by the atmosphere [33]. To address this attenuation, the use of a high-gain antenna becomes crucial. Our study specifically explores how gain is affected as a function of frequency in a free space environment, with

FIGURE 4. Fabricated antenna design.

TABLE 2. Antenna performance comparison with published works in literature.

Ref.	Antenna size (mm^3)	Type	BW (GHz)	Gain (dBi)	Applications
[32]	15.2×16.5×1.6	Microstrip	35-40	------	Glucose sensing
[33]	6.25×6.25×1.7	Microstrip	30	------	Food sensing
[34]	400×200×2	Horn	32-38	12	Rader detection
[35]	100×100×1.4	Horn	100-300	------	Remote sensing
[36]	250×250×2.1	Horn	26-60	12	Land mine detection
[37]	2.8×2.4×1.7	Microstrip	28-160	1.5-7	5G
[38]	3.5×3.5×1.2	Microstrip	38	-----	Comms.
This work	90×100×100	3D slot array	1-30	3-22.5	Comms.

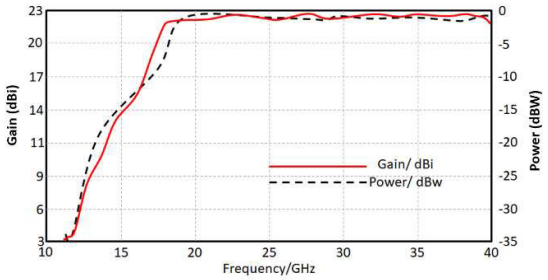

FIGURE 5. The proposed antenna performance in terms of gain and power spectra.

the transmitter positioned 10 meters away from the receiver. Fig. 5 illustrates the variations in power and gain for the proposed antenna. Notably, the antenna achieves a gain of approximately 21.5 dBi at 31 GHz with a power level of −1.2 dBw.

In the context of wireless communications, fundamental concepts include path loss and fading effects. Attenuation, a critical aspect in wireless communication systems, denotes the reduction of signal power or energy as it traverses through a medium like air, water, or solid objects. Path loss, on the other hand, refers to the decline in signal power over distance in free space without obstacles or interference. Fading encompasses variations in signal strength during propagation due to interference, reflections, and scattering.

Fading effects can lead to fluctuations in received signal strength over time, resulting in signal degradation and diminished communication performance. Two primary types of fading exist: slow fading, occurring over extended periods due to environmental changes like rainfall or cloud accumulation, and fast fading, transpiring over short intervals due to multipath propagation and rain-induced tropospheric scintillation. Fast fading involves reflections and scattering, causing constructive or destructive interference at the receiver.

Various factors influence the extent of impairments, including rain parameters (rain height, rainfall rate) and transmission parameters (frequency, modulation scheme). Frequency (f) plays a crucial role, as per the Friis transmission equation, where it is directly proportional to signal power attenuation and, consequently, the Signal-to-Noise Ratio (SNR), potentially leading to increased error rates. For frequencies below 3 GHz, ionospheric scintillation significantly affects, while frequencies above 10 GHz see substantial impact from atmospheric phenomena like rain and clouds [41].

IV. RAINFALL CHARACTERISTICS IN UAE

The Middle East, situated on the northeastern edge of the Arabian Peninsula, covers an area of approximately 83,600 km2 [42]. Comprising seven emirates, most of which border the northeastern shores of a gulf (depicted in Fig. 6), the United Arab Emirates (UAE) straddles the boundary between tropical and subtropical climates. The UAE's climate is characterized by two primary regions: a vast desert dominating the central and western parts of the country, resulting in desert-like climate attributes, and the northeastern border along the Gulf, where the presence of the sea contributes to higher humidity levels [43]. The subsidence of air in this region leads to a significant rise in average annual temperatures during the summer, making this area one of the hottest on the planet. Consequently, most rainfall in the UAE is concentrated between November and March [43].

Merabtene et al. [44] conducted extensive rainfall rate measurements in the UAE spanning over 80 years (1934 to 2014) to determine the average annual rainfall rate. However, notable changes in rainfall characteristics, especially after 1998 [45], [46], prompted a focus on measurements

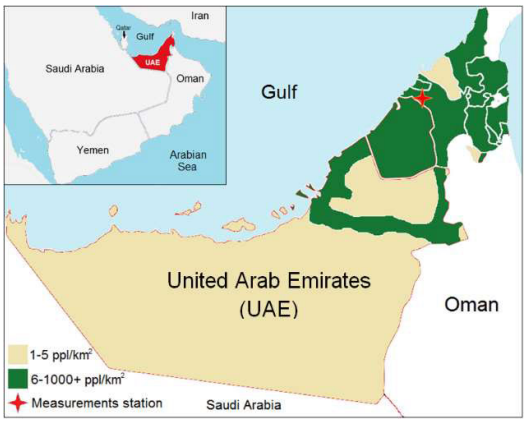

FIGURE 6. UAE map with measurements of the station location.

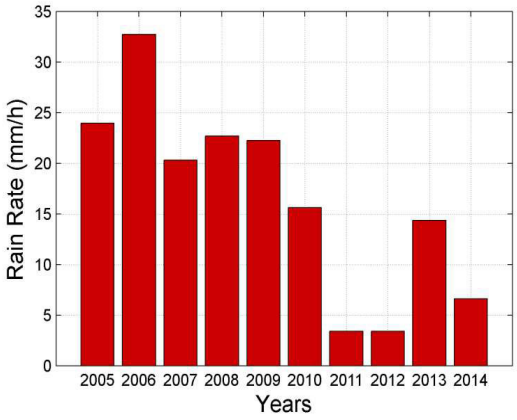

FIGURE 7. Average measured rainfall rates.

post-1998, reflecting the rain-induced impairments experienced in the UAE. Examining weather effects on satellite channels and service quality is crucial, particularly in the northeastern region where much of the population resides (as depicted in Fig. 6).

Rainfall in the UAE primarily occurs during the winter months and typically registers below 100 millimeters. Precipitation events manifest as showers, heavy rainfall, and, at times, extreme rainfall, particularly in densely populated areas like Dubai and Sharjah [44]. To capture regional nuances, rainfall rates have been closely monitored in the northeastern region, including the installation of a tipping bucket rain gauge at Sharjah International Airport. Accurate annual rainfall data is essential [20], [47], [48]. Over a ten-year period (2005 to 2014), average rainfall rates were meticulously measured and recorded, as illustrated in Fig. 7.

Data for this analysis was sourced from the Meteorological office at Sharjah International Airport [44]. Initial measurements were in millimeters and later converted to millimeters per hour (mm/h). During this decade-long observation, the maximum recorded rainfall rate was 33 mm/h in 2006, while the minimum rate of 4 mm/h occurred during the drier years of 2011 and 2012. The average measured rainfall rate over this ten-year period was determined to be 16.5 mm/h,

enhancing the accuracy of rainfall rate performance characterization for the region [47], [48].

V. PROPOSED PREDICTION MODEL OF THE RAIN IMPAIRMENTS AND CHANNEL QUALITY

This section introduces a novel model for predicting rain-induced impairments and assessing channel quality for the HTS-to-land communication channel in the UAE. The experimental setup to validate the proposed model consisted of multiple line-of-sight terrestrial links, with both the transmitter and receiver mounted on an aluminum pipe at a height of 7 meters above the ground. Each link was positioned 2.8 km apart. The transmission involved modulated signals within a carrier frequency range of 18 GHz to 40 GHz, and the maximum transmit power was set at +30 dBm. Signal levels were measured with a scalar network analyzer at 10-second intervals and systematically recorded using a data logger. To capture real-time environmental conditions, on-site rain gauges were deployed to measure the actual rainfall rate throughout the experiment.

The model consists of three algorithms designed to enhance prediction accuracy and improve overall signal quality assessment.

Algorithm 1 focuses on predicting rain attenuation over a 1 km slant path. It utilizes a modified ITU-R prediction model [23] and incorporates a novel approach called the Attenuation-Specific Data Mining (ASDM) procedure. The key innovation is the use of actual measured rainfall rate data [13], replacing the predicted values from the ITU. This substantial improvement in data accuracy results in more precise predictions of rain-specific attenuation [49] and, subsequently, HTS-to-land signal quality.

Algorithm 2 addresses the effective slant path length, adapting it based on horizontal projection adjustments and vertical length modifications, considering the specific meteorological data in the UAE [16], especially related to rain in the troposphere.

Algorithm 3 further refines the model by AI-based predicting rain-induced attenuation and its impact on HTS channel quality. It specifically evaluates the carrier-to-noise ratio and symbol error rate for five commonly used modulation schemes (QPSK, 8PSK, 16-QAM, 32-QAM, and 64-QAM). Algorithms 1 and 2 serve as the foundational input for the calculations in this algorithm. These modulation schemes were used in the single-media or multimedia communication standards like Digital Video Broadcasting via Satellite (DVB-S) and Digital Video Broadcasting via Satellite-Second Generation (DVB-S2) and (DVB-S2X) which are mostly employed worldwide [24], [50], especially in the middle-eastern countries.

Algorithm 1 calculates the rain-specific attenuation, a critical parameter for precise rain attenuation predictions [51]. This attenuation represents the electromagnetic power absorbed and scattered by rain droplets over a 1 km path, directly influenced by the transmission frequency. The coefficients, denoted as 'k' and 'α', vary based on factors like droplet size distribution, frequency, and electromagnetic wave polarization. Algorithm 2 accounts for the inhomogeneity of rain in both vertical and horizontal directions, introducing factors such as the Vertical Adjustment Factor (VAF) and Horizontal Reduction Factor (HRF) to consider temporal variations in raindrop dimensions and rain height [16]. The calculation of these factors relies on a high rainy percentage (0.01%) of annual time, reflecting the temporal variability of rain-related dimensions. To estimate the non-homogeneity of rain along the propagation path, Algorithm 2 incorporates the effective path length (L_E).

TABLE 3. Conventional telecommunication parameters.

Parameter	Value
EIRP Gr	68.5 dB 55 dBi
R_S	30 Msps
θ	45°
h_S	6m above sea level
L_{sys}	1 dB

The two algorithms are validated for different locations in the middle east [8], [52] and found to have a prominent accuracy, then - in this study – the developed Algorithm 3 is attached to algorithms 1 and 2 for the design of comprehensive channel analysis model in UAE and acquiring precise channel state information for optimizing proper fade mitigation technique by integrating a frequency diversity aware-antenna design.

The results obtained from Algorithms 1 and 2 serve as the input parameters for Algorithm 3, allowing for the prediction of rain-induced signal loss in the HTS system, with measurements given in dB/km and the effective slant path length in kilometers. A summary of the telecommunication parameters for the three algorithms is provided in Table 3, including actual measured values. Algorithm 3 is instrumental in estimating, evaluating, and analyzing the link availability and signal quality of the HTS-to-land communication channel under rainy conditions. It offers insights into long-term statistics related to rain-induced attenuation, assesses link margin through carrier-to-noise ratio, and analyzes the overall reduction in received power. The Free Space Loss (FSL) is assessed based on the transmitted frequency and link distance (d) to gauge HTS communication service quality. The subsequent analysis involves evaluating quality performance in the UAE, particularly in terms of the Symbol Error Rate (SER), which serves as a quality indicator. SER is theoretically estimated using three conventional modulation schemes frequently employed in satellite communication systems: QPSK, 8-PSK, 16-QAM, 32-QAM, and 64-QAM. This comprehensive model empowers the selection of an optimal Fade Mitigation Technique (FMT) to maintain reliable communication during rainy conditions.

VI. DISCUSSION

To detect the impact of rain-induced impairments on the HTS-to-land channel, the elevation angle is settled to a fixed value

Alogrithm1:

1. Input transmission-specific parameters (elevation angle θ, frequency f, and polarization angle τ).
2. Input actual measured rainfall rate data in millimeters (mm) and convert the average rainfall rate data on a given time interval of 1 min to mm/h.
3. Obtain frequency-dependent coefficients k and α [3]:
$$k = \frac{k_H + k_V + (k_H - k_V)\cos^2\theta \cos(2\tau)}{2}$$
$$\alpha = \frac{k_H\alpha_H + k_V\alpha_v + (k_H\alpha_H - k_V\alpha_v)\cos^2\theta\cos(2\tau)}{2k}$$
Where the empirical values related to the horizontal polarization (k_H and α_H) and vertical polarisation (k_V and α_v) are obtained from [53].
4. Calculate the rain-specific attenuation (rain-induced attenuation for 1 km slant path) using 1-min cumulative distribution rainfall rate expressed in (dB/km) [3]: $\gamma_{Rain} = \alpha(R)^k$

Alogrithm2

1. Input earth station-specific parameters (latitude φ, longitude Ł, station height h_s, elevation angle θ).
2. Input transmission-specific parameters (frequency f, and polarization angle τ).
3. Obtain zero isotherm height h_0 in UAE from ITU recommendation [54].
4. Determine the rain height [54], [55]:
$$h_R = h_0 + 0.36$$
5. Calculate the actual slant path length L_S [23]:
if $\theta \geq 5°$, then $L_S = \frac{h_R - h_S}{\sin\theta}$
otherwise,
$$A = \pi r^2 L_S = \frac{2(h_R - h_S)}{\sqrt{\sin^2\theta + \frac{2(h_R - h_S)}{E_{ER}}} + \sin\theta}$$
Where the earth's equivalent radius
$E_{ER} = 4r_e/3$ and r_e is the earth's radius in km.
6. Obtain the slant path horizontal projection.
$$P_H = L_S \cos\theta$$
7. Estimate the horizontal reduction factor HRF:
$$HRF = \frac{1}{1 + 0.78\sqrt{\frac{P_H \gamma_R}{f}} - 0.38\left(1 - e^{-2P_H}\right)}$$
8. Calculate the adjusted elevation angleξ based on planner geometry.
$$\xi = \tan^{-1}\left(\frac{h_R - h_S}{P_H\, HRF}\right)$$
9. Estimate the effective slant path through the rain L_R:
if $\xi > \theta$, then $L_R = \frac{P_H r_H}{\cos\theta}$
otherwise, $L_R = \frac{H_R - H_S}{\sin\theta}$
Estimate the vertical adjustment factor VAF:
$$VAF = \frac{1}{1 + \sqrt{\sin\theta}\left[31\left(1 - e^{-\frac{\theta}{1-\chi}}\right)\frac{\sqrt{L_R \gamma_R}}{f^2} - 0.45\right]}$$
10. Calculate the effective slant path length L_E:
$$L_E = L_R V_F$$

Algorithm 3

1. Input the telecommunication parameters.
2. From the results of Algorithms 1 and 2, calculate the predicted attenuation exceeded 0.01% of an average year:
$$A_{0.01} = \gamma_{Rain} L_E$$
3. Calculate the coefficient function β of the percentage of time [23].
if p $\geq$ 1$|\lambda| \geq 36^o$ or, then $\beta = 0$
if p $<$ 1, and $|\lambda| < 36^o$, then $\beta = 0.005\ (|\lambda| - 36)$
otherwise, $\beta = 0.005\ (|\lambda| - 36) + 1.8 - 4.25\sin\theta$
4. Predict the rain-induced loss at all rainy percentages of time:
$$L_{rain} = A_{0.01}\left(\frac{p}{0.01}\right)^{-F_P}$$
Where
$F_P = 0.655 + 0.033ln(p)$ - $0.045ln(A_{0.01}) - \beta(1\text{-}p)sin\theta$
5. Calculate the losses in free space (non-rainy environment)
$$L_{FS} = 20\log\left(\frac{4\pi d}{\lambda}\right)$$
Where d is the link distance, and λ is the signal wavelength.
6. Calculate the carrier-to-noise ratio in dB:
$$CNR = EIRP + G_r - L_{FS} - L_{rain} - L_{sys} - N$$
Where $EIRP$ is the effective isotropic radiated power, G_r is the receiver gain, L_{sys} is the system loss, and N is the noise that depends on the noise temperature and bandwidth.
7. Calculate the symbol energy to noise ratio:
$$E_S/N = CNR + 10\log\left(\frac{BW}{R_S}\right)$$
Where BW is the signal bandwidth, and R_S is the symbol rate.
8. Estimate the symbol error rate $SER\ P_{se}(E_s/N)$ for 5 modulation schemes. [56], [57].

due to its effective role on the rain attenuation value. The rain-induced attenuation is extracted for 10 years in UAE based on the proposed prediction model that considered the effective rainy conditions for a period of 10 years, as shown in Figs. 8 and 9. By calculating the mean rain-induced attenuation, the resultant prediction data is evaluated to realize a

unique performance for the UAE satellite channel at the K and Ka bands, as listed in Table 4, where the presented database of the rain-induced losses of the UAE satellite channel is exhibited from 18 GHz to 40 GHz frequencies for different rainfall intensities. Fig. 8 shows that the UAE in 2006 had the highest rain attenuation of 24 dB for the 0.01% of the annual period when the frequency of the transmitted satellite signal equals 20 GHz. This is due to a much higher rain rate that reached 33 mm/h. The channel attenuation performance decreased for the years 2005, 2007, 2008, and 2009 to be bound between 16 dB and 18 dB because the rainfall rates in those years were between 21 mm/hr and 24 mm/hr. Whereas the predicted rain attenuation in the dry years of 2011 and 2012 is approximately 4 dB and is raised to 6 dB in 2014.

It is known that the UAE shares borders with the gulf from the north side and contains a vast desert that dominates 70% of the entire country on the east-western side [58], affecting the nature and direction of the monsoon. Consequently, unique atmospheric parameters are introduced. The intense rainfall rate times happen in 0.001% of the year, roughly the highest 9 hours/year rainfall rate. At these times, the induced loss increased significantly to reach approximately 42 dB in 2006 and 29 dB to 33 dB in the years 2005, 2007, 2008, and 2009. To a lesser extent, the rain attenuation reaches lower levels at the rest of the period of interest, which reflects the lower and normal rainfall rate in the UAE. The value of the rain-induced loss increases with the increase of the transmission frequency. The plot of rain-induced loss of HTS signal at higher frequencies can visualize the effect of transmission frequency. The predicted rain-induced loss values at 30 GHz are shown in Fig. 9 for the period of 10 years. At present, 20 and 30 GHz are the usual frequencies for transmitting data to and from satellite systems, respectively. Fig. 9 demonstrates that in the rainiest year of 2006, there was a rain attenuation of up to 50 dB 0.01% of the time. The values of rain-induced attenuation were between 34 dB and 39 dB in the wet years 2005–2009 at 30 GHz. However, it was discovered that the rainfall rate was extremely high, resulting in rain attenuation of up to 82 dB at 0.001% of the time in 2006. In contrast, the dry sky of 2011 and 2012 had rain attenuation limited to 16 dB. This could pose a severe risk to the satellite link's availability. The connection of an earth station to a different satellite led to a variation in the rain attenuation due to an alteration in the elevation angle θ. Moreover, the present study investigated the effect of changes in elevation angle on the rain attenuation prediction in the UAE, even when the earth station is connected to the same satellite. Figs 10 and 11 depicted the impact of different elevation angles on rain-induced attenuation prediction in the UAE.

Figs. 10 and 11 illustrate that the rain induced attenuation increases as the angle of elevation decreases. It has been observed that, when operating at 20 GHz with an elevation angle varying from 80° to 20°, the signal attenuation at 0.01% of the time is in the range of 11 dB to 25 dB because of the increase in the slant path length, thus requiring the signal to traverse a higher significant number of rain droplets. In contrast, the elevation angle varies from 21 to 35 dB for the most extreme rainfall rates of 0.001% of the year. At 30 GHz, the rain induced effects on satellite link become relatively higher. The rain attenuation reaches 52 and 68 dB for elevation angle of 20° at heavy and extreme rainfall rate periods, respectively. Whereas for a high elevation angle, 80°, the attenuation reaches 40 dB at extreme rainfall rate and 24 dB at heavy rainfall rate at 0.01% of time. Moreover, as the elevation angles increased, the convergence of the attenuation performances increased simultaneously. This high difference in rain-induced attenuation between the low and high elevation angles reflects the paramount consideration that should be considered in the design of the HTS-to-land channel and the need for implementing the proposed model.

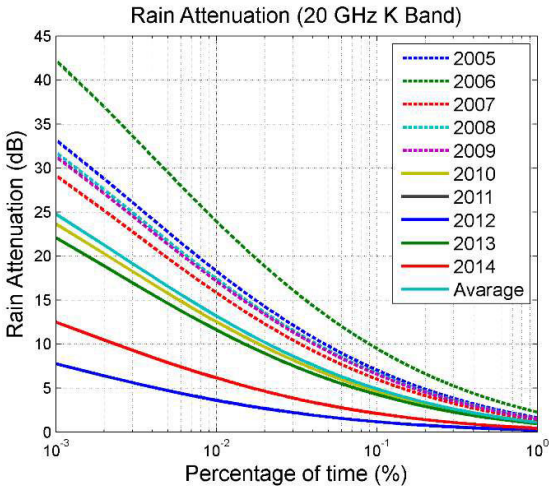

FIGURE 8. Rain induced attenuation at 20 GHz.

As the intensity of the rainfall increased, there was a notable diminishment in the signal strength, which can be best expressed as a signal carrier-to-noise ratio CNR [59]. Since the proposed antenna covers a wide range of frequencies with a stable gain, the authors conducted an exterminate to switch the frequency of operation from 20 GHz to 30 GHz to realize the effects of that on the CNR as Fig. 12. It is obvious the value of the evaluated CNR at 20 GHz, in general is higher than the one at 30 GHz. Therefore, to mitigate the effects of rain, using the communication link at 20 GHz is more feasible.

The impact of rain on satellite signals is evident, particularly affecting the received signal level and, consequently, the Carrier-to-Noise Ratio (CNR), especially at higher rainfall rates. At a frequency of 20 GHz, rain-induced impairments can reach approximately 18 dB for heavy rainfall and up to 30 dB for extreme rainfall rates. Notably, link availability becomes nonexistent at 30 GHz during periods of high rainfall rates. This underscores the necessity for implementing Fade Mitigation Techniques (FMT), as depicted in Fig. 12, but such implementation is required for less than 0.1% of the rainfall time.

TABLE 4. Proposed database of rain-induced loss on a satellite channel in UAE for an average of 10 years.

Frequency (GHz)	Rain-induced loss (dB)		
	Moderate rainfall p=0.1%	Heavy rainfall p=0.01%	Extreme rainfall p=0.001%
18	3.9	10.7	20.4
19	4.4	11.9	22.6
20	4.9	13.2	24.7
21	5.5	14.5	27.0
22	6.0	15.9	29.3
23	6.6	17.4	31.7
24	7.3	18.8	34.1
25	7.9	20.4	36.5
26	8.6	21.9	39.0
27	9.3	23.5	41.6
28	10.0	25.1	44.1
29	10.7	26.8	46.7
30	11.5	28.4	49.3
31	12.2	30.1	51.9
32	13.0	31.8	54.5
33	13.7	33.5	57.0
34	14.5	35.2	59.6
35	15.3	36.8	62.1
36	16.0	38.5	64.6
37	16.8	40.1	67.1
38	17.5	41.8	69.6
39	18.3	43.4	72.0
40	19.0	45.0	74.4

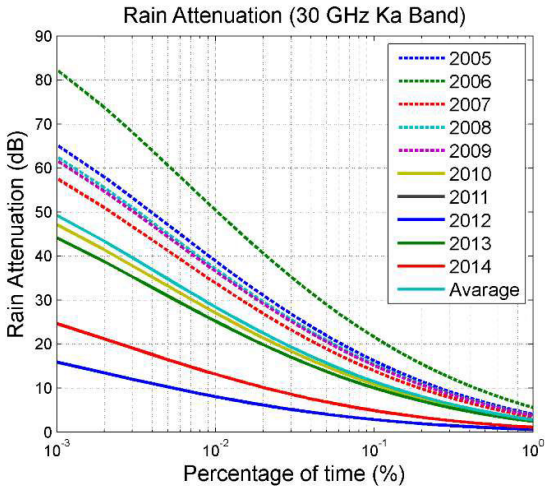

FIGURE 9. Rain induced attenuation at 30 GHz.

Additionally, rain significantly influences transmission error rates. With an increase in the rainfall rate, the Symbol Error Rate (SER) rises simultaneously. Assuming no error correction is applied, the rain-induced SER on the HTS-to-land signal is evaluated for three conventional modulation schemes, as illustrated in Fig. 13. Both the transmission frequency and the type of modulation scheme exert substantial impacts on SER. Specifically, the SER reaches 0.9 at the extreme rainfall rate, occurring in 0.001% of time, for the highest (64-QAM) modulation scheme. In contrast, the SER is relatively lower for lower M-ary modulation schemes, reaching SER values of 0.59, 0.27, and 0.1 for 32-QAM, 16-QAM, and 8-PSK, respectively, under extremely high rainfall rates. For QPSK, the rain-induced SER at 20 GHz has a negligible effect but exponentially increases for less than 0.001% of time under extreme rainfall rates.

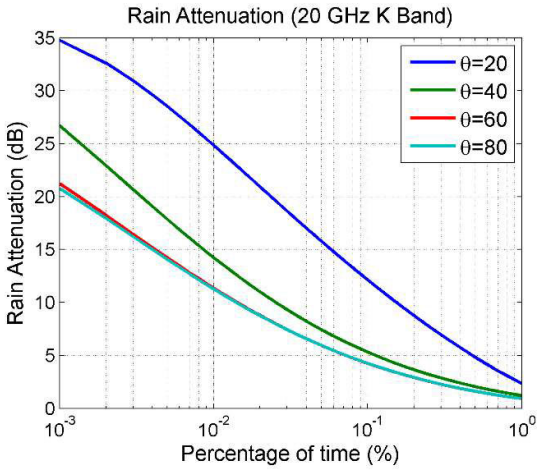

FIGURE 10. Rain induced attenuation for different θ at 20 GHz.

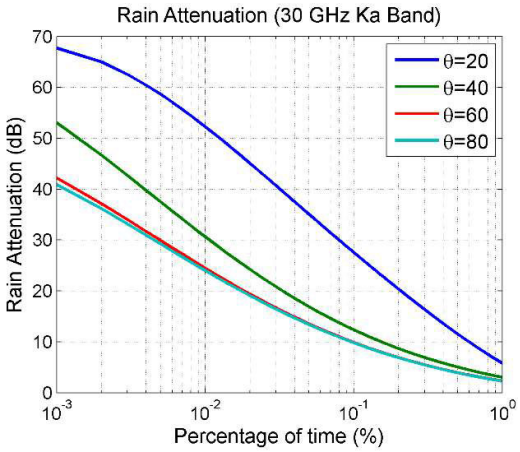

FIGURE 11. Rain induced attenuation for different θ at 30 GHz.

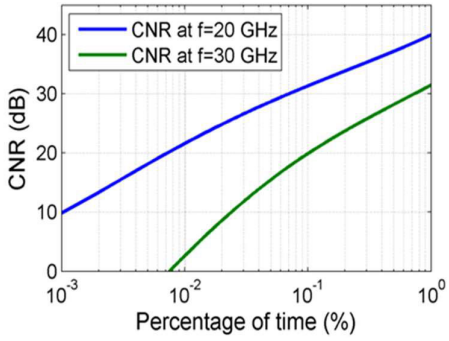

FIGURE 12. Carrier-to-noise ratio for different transmission frequencies as a function of rainfall perctenage of time.

UAE has a relatively low rainfall rate compared to most tropical countries that experience a severe problem of rainfall events at the K and Ka frequency bands. However, under extreme rainfall conditions it is recommended that FMT such as frequency diversity be employed.

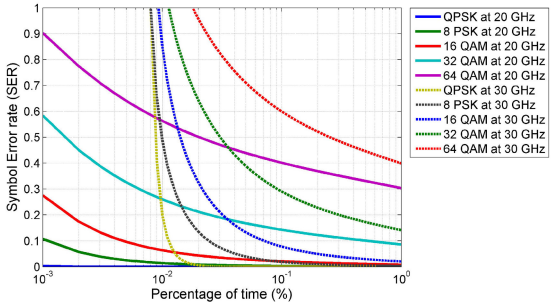

FIGURE 13. Symbol error rate for different frequencies and modulation schemes.

VII. CONCLUSION

The AI prediction and mitigation of rain-induced attenuation play a crucial role in establishing effective high-throughput satellite (HTS) communication links, especially at frequencies exceeding 17 GHz. This study offers the inaugural estimate and forecast of link-level availability for HTS in the UAE, utilizing channel quality. It proposes an AI-based frequency diversity antenna model as a fade mitigation technique. Using actual rainfall rate data, the model incorporates three AI algorithms to determine rain-induced fade levels, Carrier-to-Noise Ratio (CNR), Energy per Symbol to Noise Power Spectral Density Ratio (Es/N), and the probability of symbol errors for five modulation schemes. Covering a decade of channel measurements, the study presents the average rain-induced fade level and creates a detailed database of losses at various frequencies and rainfall intensities. The analysis of rainfall impact on HTS links in the UAE, considering different transmission frequencies and elevation angles, reveals the significant influence of elevation angles on link quality. Transmission frequency proves notably effective during intense rainfall, affecting link availability at higher modulation schemes. The study recommends employing the proposed model during rainfall events for enhanced HTS channel quality, suggesting its adoption by system designers and channel providers in the UAE. Furthermore, the paper introduces a prediction model for rain-induced attenuation and channel quality in the high-throughput satellite channel in the UAE. Validation results affirm the model's effectiveness in predicting rain attenuation impacts on satellite link performance, providing accurate channel quality predictions to optimize satellite link design and operation. The research contributes valuable insights to satellite communications, emphasizing the proposed antenna's feasibility in mitigating rain effects by allowing a seamless frequency switch within a broad bandwidth from 12 GHz to 40 GHz, maintaining stable gain around 22 dBi. Extension of this research is suggested to include other modulation schemes, covering diverse geographic locations, and conducting experimental measurements of satellite signal attenuation during rainy environment to robustly validate the rain induced attenuation analysis and prediction.

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