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Future Terrestrial Communication Links Attenuation Synthesis based on Crane and ITU Rain Models at Microwave and Millimeter-wave links

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Abstract:
Rain- induced attenuation is one of the most critical impairments for terrestrial wireless links operating above 10 GHz. With the rapid deployment of 5G, the emergence of 6G, and the increasing demand for back- haul and fronthaul services in the millimetre- wave (mm- wave) spectrum (30–300 GHz), accurate prediction of rain attenuation becomes essential for reliable network planning and adaptive link- budget design. With the rapid evolution of terrestrial communication systems, especially high-capacity microwave and millimeter-wave links, precise prediction of rain-induced signal attenuation has become increasingly crucial. As next-generation networks transition toward higher frequencies (e.g., above 10 GHz), atmospheric impairments such as rain attenuation significantly affect system reliability and link availability. This paper presents a comprehensive comparative analysis between two prominent rain attenuation models: the International Telecommunication Union (ITU-R) model and the Crane Global Model. Through theoretical exploration, simulaton and practical implementation, with a case study utilizing real-time rainfall data, we evaluate the atenuation estimation of both models across various frequencies, path lengths, rain rates, elvation angle andtilt agle askey parameters. The results show that models exhibit strong frequency dependence, with attenuation increasing as frequency and rain rate increases. However, the rate of increase and the coefficients involved differ, necessitating careful consideration when choosing a model for specific applications. .

Keywords: Rain Attenuation, Terrestrial Communication Links, ITU-R P.618, Crane Model, Millimeter-wave Propagation, 6G, Link Reliability, Comparative Study

1. Introduction

The deployment of future terrestrial communication networks is advancing rapidly, driven by exponential growth in data demand and the integration of technologies such as 5G-Advanced and pre-6G systems. These networks increasingly rely on high-frequency bands millimeter waves (mmWave) and sub-terahertz (sub-THz) to achieve multi-Gbps data rates and ultra-low latency. Microwave (1 GHz – 300 GHz) and millimeter-wave (30 GHz – 300 GHz) frequencies present unique advantages, including broader bandwidth and increased data rates. However, atmospheric phenomena, particularly rainfall, pose significant challenges to signal integrity, leading to attenuation of the transmitted signals. Attenuation results from both scattering and absorption of electromagnetic waves by raindrops. Rain attenuation becomes a dominant factor in link budget calculations above 10 GHz and can lead to outages or degraded service quality if not accurately modeled.

Two of the most widely used rain attenuation models for terrestrial line-of-sight (LOS) links are the International Telecommunication Union Radiocommunication Sector (ITU-R) Recommendation P.618 and the Crane Global Model (also known as the Crane Two-Component Model). While both models aim to predict path-averaged attenuation due to rain, they differ fundamentally in their theoretical foundations, input parameters, and geographical adaptability.

This paper presents a comparative analysis of the ITU-R and Crane models, evaluating their performance in determining rain attenuation for future terrestrial communication systems. We will explore their applicability, limitations, and differences for various microwave and millimeter-wave frequencies, providing insights into improving link design and performance.

The remainder of this paper is organised as follows. Section 2 reviews the theoretical basis of the two rain- attenuation models. Section 3 details the methodology, including model- parameter information and definition. Section 4 presents the results, comparing attenuation statistics across frequencies, distances, elevation agles, and tilt angles. Section 5 concludes te study and als reveals future research directions.

2. Background and Related Work

2.1 Microwave and Millimeter-wave Communication

Microwave and millimeter-wave frequencies are often employed in applications such as satellite communication, wireless broadband, and point-to-point links. The advantages of these frequency bands include increased channel capacity, reduced antenna size, and lower latency. However, propagation impairments have been observed, particularly in rain-prone regions. Consequently, understanding and mitigating these impairments are crucial for maintaining system reliability.

2.2 Atmospheric Attenuation

In terrestrial communication, signal attenuation caused by atmospheric conditions, particularly rainfall, can significantly affect system performance. Attenuation results from both scattering and absorption of electromagnetic waves by raindrops. This phenomenon becomes more pronounced at higher frequencies, necessitating precise modeling to predict link performance under various weather conditions.

2.4. Rain Attenuation in Terrestrial Links

Rain attenuation occurs when electromagnetic waves are absorbed and scattered by raindrops along the propagation path. The attenuation depends on the rain rate, R (mm/h), frequency, polarization, temperature, and drop size distribution (DSD). The specific attenuation (γ) is generally modeled as:

$$\gamma = kR^{\alpha} \tag{1}$$

where (R) is the rain rate, and (k) and (α) are frequency- and polarization-dependent coefficients derived empirically or from Mie scattering theory.

The total path attenuation is obtained by integrating γ along the link path, adjusted for the effective rain length due to non-uniform rainfall distribution.

2.5. ITU-R Rain Attenuation Model (P.618-14)

The ITU-R P.618 recommendation provides a standardized procedure for estimating rain attenuation for Earth-space and terrestrial paths. Key steps in the ITU-R model for terrestrial links include:

- Determination of rain rate (R_{0.01}) (rain rate exceeded 0.01% of the time annually).
- Calculation of specific attenuation using (k) and (α).
- Computation of the effective path length (L_E) and reduction factor (r) in connection with the rain rate.

For ITU-R P.618-14 model, the path length is given by:

$$L_E = L_S \cdot r \cdot v \qquad (2)$$

with r and L_S being defined by:

$$r = \frac{1}{0.874 + 0.0255\left(R^{0.54} - 1.7\right)L_G^{0.7}} \qquad (3)$$

$$L_S = \begin{cases} \dfrac{h_R - h_S}{\sin\theta} & \text{for } \theta \geq 5^\circ \\ \dfrac{2(h_R - h_S)}{\left(\sin^2\theta + \dfrac{2(h_R - h_S)}{R_e}\right)^{1/2} + \sin\theta} & \text{for } \theta < 5^\circ \end{cases} \qquad (4)$$

The horizontal projection of the slant path length along the ground is given by:

$$L_G = L_S \cos\theta \qquad (5)$$

The slant-path attenuation is then given by:

$$A = L_E \gamma \qquad (6)$$

where v is a vertical adjustment factor

2.6. Crane Rain Attenuation Model

Developed by Dr. William L. Crane in the 1980s, the Crane model is physically based and considers the three-dimensional structure of rain cells. The model defines rain zones (convective and stratiform) and varies attenuation based on link geometry, cell size, and storm height. The model uses a path attenuation integral over a non-uniform rain cell model, providing better spatial resolution than ITU-R. The general effective path length for the Crane mode is of the form:

L_E = Y(e^{yD}-1)/y, *for* 0<D<δ (7)

L_E = Y($e^{y\delta}$-1)/y+$b\alpha e^{zD}$/y, *for* δ<D< 22.5 km (8)

Other key parameters of the model are defined by are difined by:

$b = 2.3R^{-0.17}$ (9)

$c = 0.026 - 0.03\ln R$ (10)

$\delta = 3.8 - 0.6 \ln R$ (11)

$u = \ln (be^{c\delta})/\delta$ (12)

$y = \alpha u$ (13)

$z = \alpha c$ (14)

The model accounts for vertical rain profile via a height-dependent reduction factor. As seen above, the Crane's model requires more input parameters, including storm cell dimensions and altitude.

2.7. Previous Comparative Studies

Several studies have compared ITU-R and Crane models primarily in satellite communication contexts. For instance, Ajayi and Owolawi (2016) evaluated both models in Nigeria and found Crane more accurate in tropical regions. Similar investigation are also contained in Ituabhor et al, (2022), Seyi et al, (2023), Isabona and Srivastava, (2016), Ebhota et al, (2018), Peng et al (2019), Isabona and Ojuh, (2015), Joseph (2019), Ugbeh, (2025), Ekpenyong and Isabona (2010). Other studies in Southeast Asia and Brazil have reported similar trends. However, these comparisons are largely outdated and focused on lower frequencies (Ku/Ka bands). Few recent studies have addressed mmWave bands or terrestrial links above 30 GHz under future network scenarios.

3. Methodology

3.1. Model Implementation and Parameters

Both models were implemented in MATLAB for simulation and comparison. Input parameters include:

- Frequency range: 10–100 GHz
- Path length: Varied
- Polarization: Horizontal
- Climatic zones: Tropical area of Nigeri
- Rain rate data: Derived from ITU-R P.837-7 and local meteorological records
- Elevation angle: Varied
- Data spanned 2018–2023 and included high-resolution time-series (1-min intervals) of rain rate and received signal levels.
- For the ITU-R model, rain rate (R_{0.01}) was obtained from ITU-R P.618-14. k and α were computed from ITU-R P.838-3.
- Crane's model, storm cell parameters were set based on regional thunderstorm statistics:

4. Results and Discussion

This section provides attenuation estimation details with respect to frequency, path length, rain rates, tilt angle and elevation angles. Fig. 1 show that both the Crane and ITU-R rain attenuation model estimation increases with frequency in the 1-1000 GHz range. The primary difference lies in how each model accounts for the spatial non-uniformity of rain over a link distance (the effective path length), which leads to different total attenuation predictions. Their variation with frequency generally decreases as frequency increases, resulting in higher specific attenuation at higher frequencies for a given rain rate, R. This means a signal propagating at 40 GHz will experience more attenuation per kilometer than a signal at 10 GHz for the same rain rate. As observed from the graphical figure, the ITU-R Model typically assumes a more uniform rainfall environment or uses an effective propagation distance, leading to generally lower total attenuation predictions compared to the Crane model, especially at higher frequencies and longer path lengths

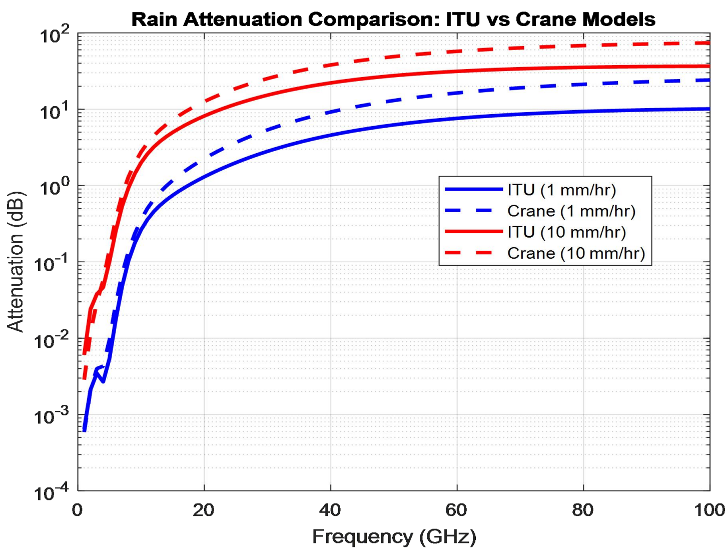

Fig.1: The Crane and ITU-R rain attenuation model estiamtion with frequency in the 1-1000 GHz range

Fig.2: Both Crane and ITU-R models reveal increasing rain attenuation with higher rain rates (R) and frequencies, using the power law model, $Y=kR^{\alpha}$, ang with key compuation parameters. Also, the

graphical Fig. reveals that the Crane model attained attained higher attenuation estimation than the ITU-R model at lower rain rates. However, the estimation gap between the two models are clealy seen at higher rain rates. The Crane model may produce overestimates in regions with variable rain intensities since it does not account for non-linear rain distributions. Meanwhile, the ITU model may underestimate attenuation in certain localized conditions due to its reliance on average rainfall data

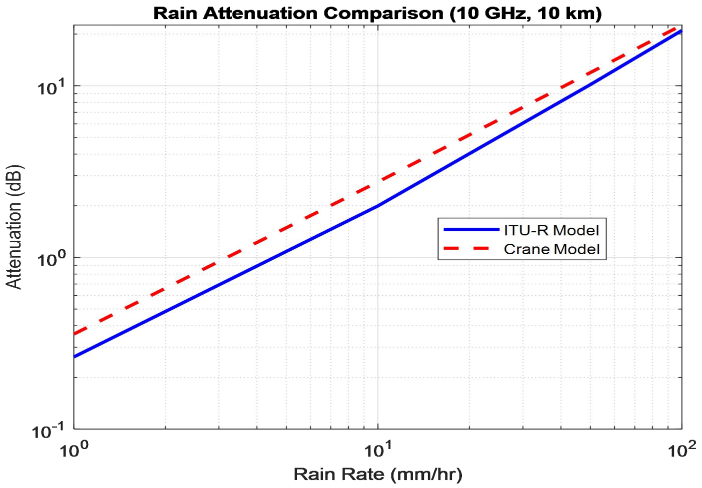

Fig.2:the Crane and ITU-R rain attenuation model estiamtion with rain rate in mm/hr

Both the Crane and ITU-R rain attenuation models calculate total path attenuation by multiplying the specific attenuation (dB/km) by an effective propagation distance that accounts for the non-uniform, cellular nature of rain. The primary difference is the specific mathematical functions and parameters used for this effective distance (or path-to-path conversion factor), which causes the models to vary differently with increasing path length as observed in Fig. 3. For example, the ITU-R Model (P.838) using a simpler effective path length factor, the total attenuation generally shows a more linear, though slightly sub-linear, increase with path length (for typical ranges and rain rates). Thus, it predicts lower attenuation values compared to the Crane model, especially at higher frequencies and longer ranges. The ITU model is widely applicable globally, accounting for rain height variations with latitude and longitude. The Crane model is more complex, using two exponential functions to model different rain regions (heavy core and lighter surrounding rain). This approach better accounts for the cellular nature of rainstorms and often predicts higher attenuation values than the ITU-R model, especially in North America for which it was primarily developed. In overall, the graphical Fig. reveals that the Crane and the ITU-R model attained same attenuation estimation values at lower path lengths However, the estimation gap between the two models increases at higher path lengths

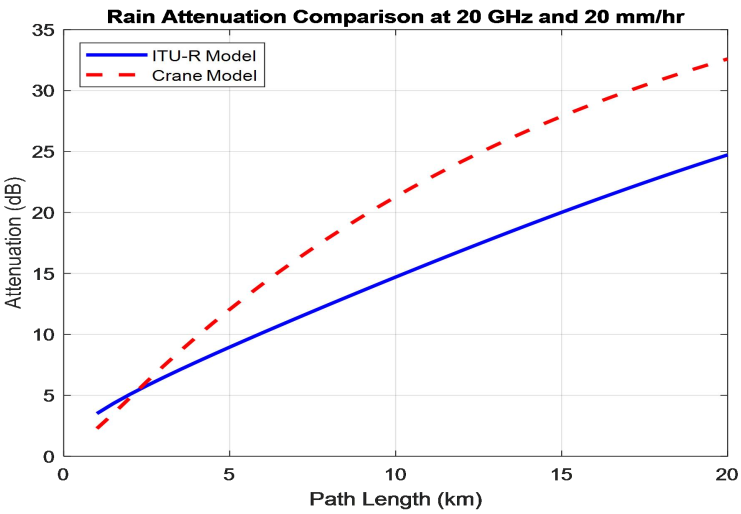

Fig.3: The Crane and ITU-R rain attenuation model estiamtion with Path length in km

The Figs. 4-7 below show that both the Crane model and the ITU-R models calculate rain attenuation that varies significantly with polarization tilt angle (τ), especially at higher frequencies and low elevation angles, with generally lower attenuation for slant polarization (closer to 45°) and higher for horizontal/vertical (0°/90°), due to raindrop oblateness, with the Crane model. Raindrops are oblate (flattened), not spherical, causing different attenuation for horizontal/vertical polarizations compared to circular. The Figs. Show that the attenuation decreasing as the tilt angle moves from 0° (horizontal) towards 45° (circular), then increasing again towards 90° (vertical). Hence, maximum attenuation often occurs at horizontal (0°) or vertical (90°) polarization, with minimum attenuation near 45° (circular).

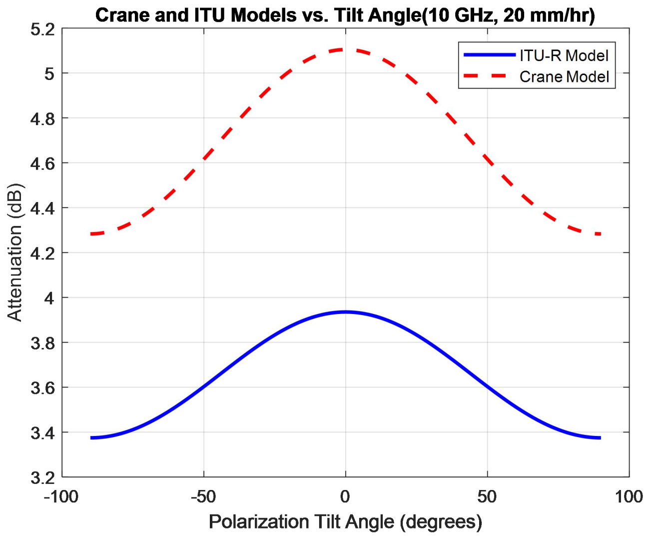

Fig.4:The Crane and ITU-R rain attenuation model estiamtion versus Tilt agle at 10GHz frequency and 20mm/hr rain rate

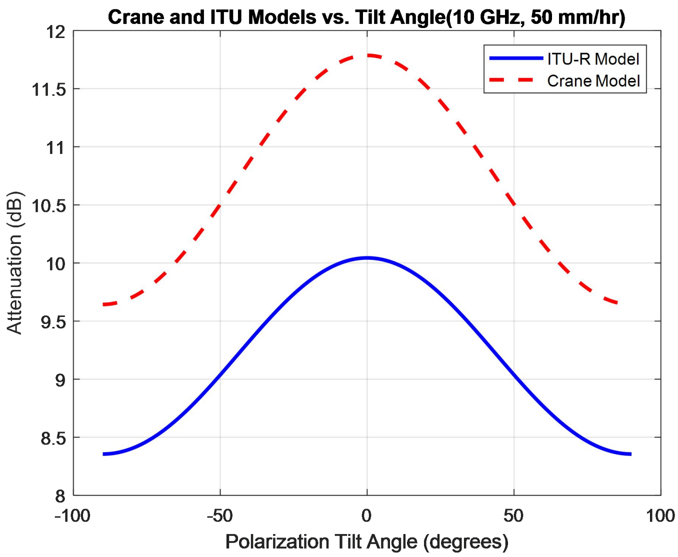

Fig.5:The Crane and ITU-R rain attenuation model estiamtion versus Tilt agle at 10GHz frequency and 50mm/hr rain rate

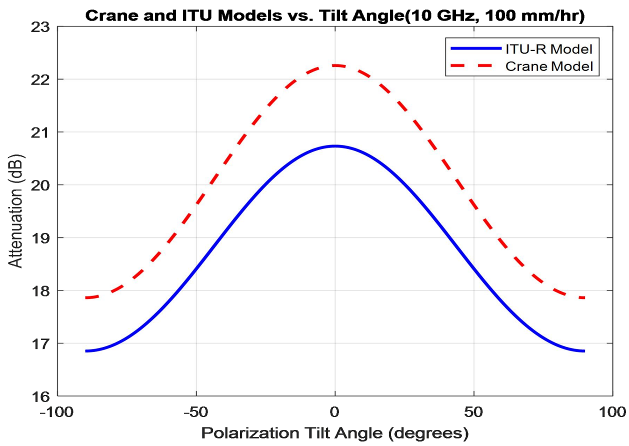

Fig.6:The Crane and ITU-R rain attenuation model estiamtion versus Tilt agle at 10GHz frequency and 100mm/hr rain rate

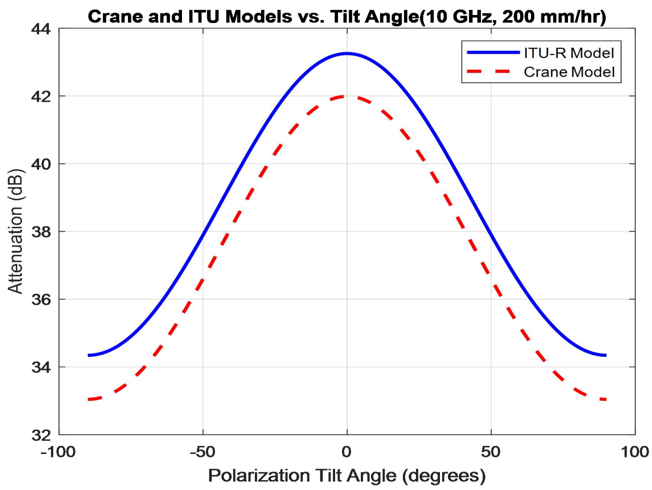

Fig.7: The Crane and ITU-R rain attenuation model estiamtion versus Tilt agle at 10GHz frequency and 200mm/hr rain rate

The Figs. 8-11 show that both the Crane model and the ITU-R models calculate rain attenuation that varies significantly with elevation angle. The Figs. Reveals that as elevation angle increases (moving from horizontal to vertical), the slant path through the rain layer shortens, reducing total attenuation in both models, especially for ITU-R's effective path concept. Here, the graphical Figs. reveal that the Crane model attained higher estimation values compared to the the ITU-R model. However, the estimation gap between the two models reduces as the rain rates rose to higher number.

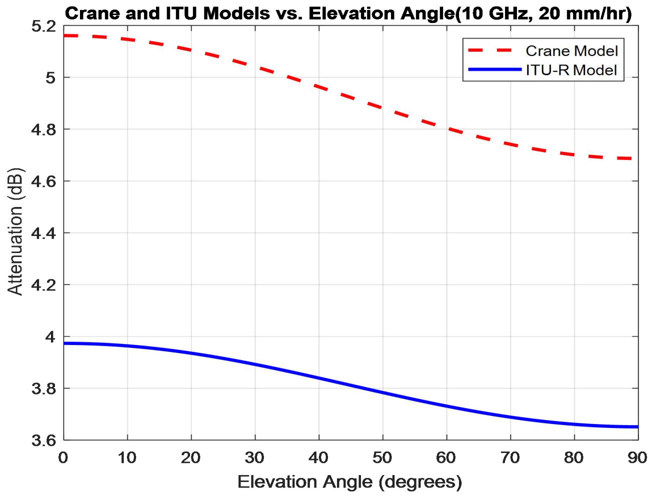

Fig.8: The Crane and ITU-R rain attenuation model estiamtion versus Elevation angle at 10GHz frequency and 20mm/hr rain rate

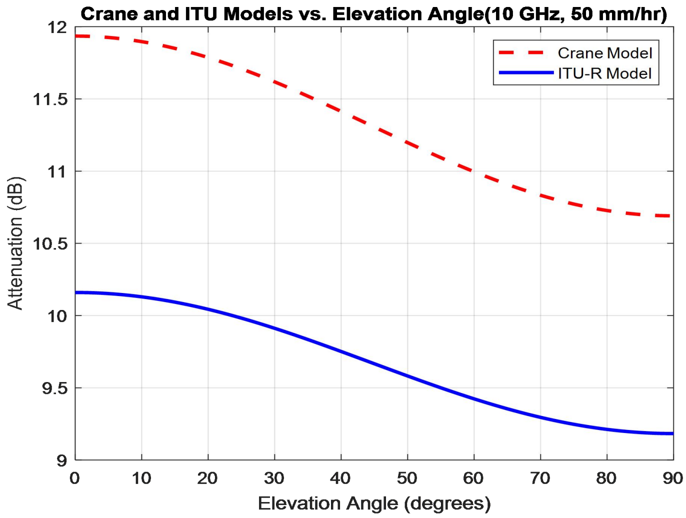

Fig.9: The Crane and ITU-R rain attenuation model estiamtion versus Elevation angle at 10GHz frequency and 50mm/hr rain rate

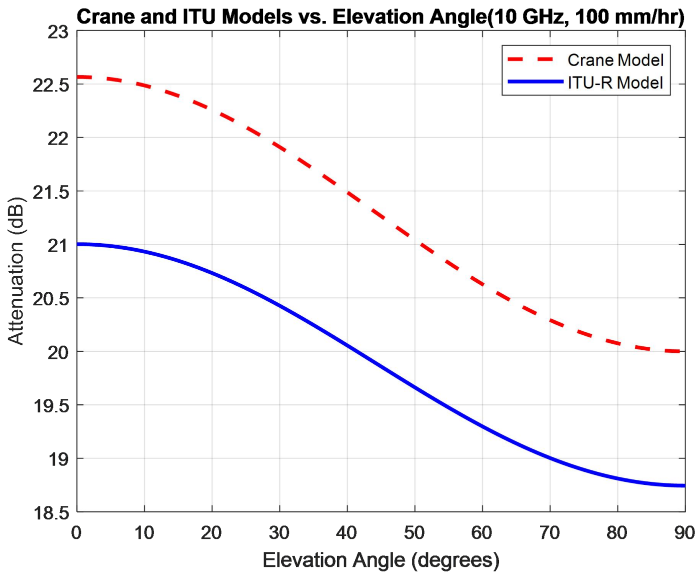

Fig.10: The Crane and ITU-R rain attenuation model estiamtion versus Elevation angle at 10GHz frequency and 100mm/hr rain rate

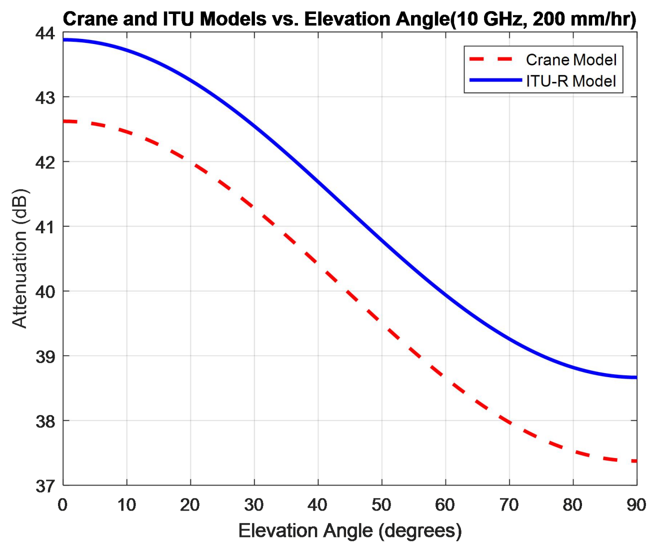

Fig.11: The Crane and ITU-R rain attenuation model estiamtion versus Elevation angle at 10GHz frequency and 200mm/hr rain rate

In general, the Crane outperforms ITU-R due to its ability to model convective cells common in tropical climates. ITU-R tends to overestimate attenuation at moderate rain rates (>30 mm/h) and underestimates peak events due to simplified spatial averaging.

5. Conclusion

This comparative study highlights the importance of selecting appropriate rain attenuation models for terrestrial communication link design. While the Crane model offers simplicity, the ITU model provides a more accurate representation of rain-induced attenuation, particularly at higher frequencies and under various rainfall conditions. As communication systems evolve towards higher frequencies and more sophisticated services, the choice between models should be context-dependent for netwok planning. This study examined the attenuation characteristics across various frequencies (1–100 GHz), ran rates, path lengths, elevatin angles and tilt anges, highlighting their implications for futurecomunication systems. As 6G networks push into the sub-THz regime and rely on ultra-reliable low-latency communication (URLLC), the adoption of physics-based models such as Crane augmented with real-time meteorological data will become increasingly necessary. To improve the accuracy of attenuation estimimations for cellular networks, a hybrid approach integrating both models could be employed. Moreover, real-time weather data acquisition systems, such as weather radars and satellite observations, could enhance the calibration of these models for localized conditions. Simulations using various rainfall scenarios and frequency bands will also provide deeper insights into potential weaknesses in link designs.

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