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Quantification of Wet Antenna Attenuation Due to Rainfall Intensity on Cellular Microwave Communication Links

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Abstract: The performance of terrestrial microwave communication links, which serve as critical components in backhaul networks for cellular systems, is significantly affected by hydrometeorological conditions, particularly rainfall. While rain-induced attenuation along the propagation path has been extensively studied, comparatively less attention has been given to wet antenna attenuation (WAA)—additional signal losses occurring at the antenna surface due to the accumulation of water films. This paper presents a detailed quantification of WAA as a function of rainfall intensity, link frequency, and antenna characteristics. Using theoretical analysis and empirical modeling based on ITU-R recommendations and field measurements, the study establishes relationships that can be used to improve link availability predictions and adaptive power control strategies in modern cellular networks.

Keywords: Wet antenna attenuation, rainfall intensity, microwave link propagation, radome, path attenuation, cellular backhaul networks.

1. Introduction

Microwave communication links form the backbone of modern wireless communication systems, including cellular networks [1-3]. These links operate at frequencies typically ranging from a few gigahertz to tens of gigahertz, offering high bandwidth and capacity. However, their performance is heavily influenced by atmospheric conditions, which can lead to signal attenuation, commonly referred to as "rain fade." While rain fade is primarily attributed to absorption and scattering by raindrops within the propagation path (rain attenuation), a secondary and often overlooked phenomenon is the attenuation caused by water accumulated on the radiating elements of the antenna itself – wet antenna attenuation. Unlike rain attenuation, which is a volume effect, wet antenna attenuation (WAA) is a surface effect localized to the antenna aperture. Its impact can be significant, particularly for high-gain antennas commonly used in point-to-point microwave links, affecting the overall link budget and potentially causing service degradation or outages.

Thus, understanding and quantifying WAA is essential for accurate link budget calculations, quality monitoring, and the interpretation of microwave link rain measurements used in rainfall estimation and environmental monitoring. This study aims to quantify WAA as a function of rainfall intensity, employing empirical approaches that can be integrated into propagation models. Although several studies (e.g., [4–13]) have provided preliminary measurements of WAA, there is no consensus on its magnitude, frequency scaling, or dependence on rainfall intensity for modern cellular backhaul equipment.

This paper aims to provide a comprehensive analysis of wet antenna attenuation on cellular microwave communication links, with a specific focus on its correlation with rainfall intensity, transmission lengths and frequency., ween theoretical propagation models and real-world performance degradation, aiding in robust network design. We will delve into the physical principles governing this phenomenon, review existing theoretical and empirical models, and outline a framework for its quantification.

2. Theoretical Framework

2.1 Literature Review

While path rain attenuation has been extensively studied and modeled by organizations like ITU-R [1], the specific quantification of WAA for cellular microwave links is less mature. Early research on WAA primarily focused on satellite ground stations and larger parabolic antennas.

Many studies acknowledge WAA but often treat it as a residual component of total rain attenuation or lump it into a fixed "wetting loss" or "radome loss." For instance, ITU-R P.618 [6] briefly mentions radome attenuation, including that due to water film, but does not provide a detailed model for its dependence on rainfall intensity. ITU-R P.838 [1] models specific rain attenuation for the path, but not for the antenna aperture itself.

Some researchers have attempted to quantify WAA through experimental measurements studies. Zavisa et al. (1998) conducted experiments on 18 GHz and 38 GHz links using horn antennas, demonstrating significant WAA [4]. Their work highlighted the non-linear increase of WAA with rain rate.

Ohlmer et al. (2002) investigated WAA on 38 GHz terrestrial links, finding that WAA could contribute up to 3 dB in heavy rain for specific antenna/radome combinations [7]. Moupfouma (2004) proposed an empirical model for radome attenuation due to rain, based on rain rate, frequency, and radome material, specifically for satellite earth stations [5].Al-Nuaimi et al. (various) have contributed to understanding various propagation impairments, including those related to wet surfaces, emphasizing the need for comprehensive models [8]. More recent work has started to focus on higher frequencies relevant to 5G [9, 10]. These studies often use quasi-analytic models or empirical fitting to experimental data [11-16].

2.2 Rain Attenuation on Propagation Path

The specific attenuation, γ (dB/km), due to rain along the propagation path is generally modeled as:

$$\gamma = k R^{\alpha} \qquad (1)$$

where (R) is the rainfall rate (mm/h), and (k) and α are frequency- and polarization-dependent coefficients obtained from ITU-R Recommendation P.838.

2.3 Modeling Approaches

Two major modeling strategies exist:

Empirical Regression Models: derive WAA directly from observed excess attenuation correlated with rain intensity.

Electromagnetic Simulation Model: simulate wave interaction with water films using dielectric-layer theory.

The empirical approach is preferred in operational networks due to its implementation simplicity and reliance on measurable quantities.

2.4 Physical Mechanisms of Wet Antenna Attenuation

The presence of a dielectric layer, such as water, on the surface of a microwave antenna can induce several effects that lead to signal attenuation:

(i) **Impedance Mismatch:** The radiating aperture of an antenna is designed to efficiently couple electromagnetic energy into free space or from free space into the antenna. Introducing a layer of water with different dielectric properties than air creates an impedance mismatch at the antenna-water interface and the water-air interface. This mismatch causes a portion of the incident or outgoing electromagnetic wave to be reflected back into the antenna (or towards the source), rather than being radiated or received. This reflected power represents a loss of signal energy.

(ii) **Scattering:** Water on the antenna surface can form irregular structures (e.g., droplets, rivulets, continuous films of varying thickness and uniformity). These irregular shapes can scatter the electromagnetic waves, redirecting energy in unintended directions, thus reducing the power delivered to the intended receiver or radiated towards the intended transmitter.

(iii) **Absorption:** Water is a lossy dielectric at microwave frequencies. The electromagnetic energy that penetrates the water layer can be absorbed by the water molecules, converting into heat. This absorption contributes to signal attenuation. The dielectric properties of water, including its permittivity and conductivity, are frequency-dependent and also vary with temperature.

(iv) **Surface Wave Excitation:** In some cases, the water layer can act as a dielectric waveguide, supporting surface waves that propagate along the antenna surface and then radiate away in unwanted directions, or are dissipated due to losses in the water.

The interplay of these mechanisms determines the overall wet antenna attenuation. The magnitude of the attenuation is influenced by several factors:

(v) **Rainfall Intensity:** Higher rainfall intensity generally leads to a thicker and more continuous water film on the antenna surface, increasing the impedance mismatch and absorption.

(vi) **Antenna Type and Geometry:** The shape, size, and material of the antenna aperture significantly affect how water accumulates and interacts with the electromagnetic fields. For example, parabolic reflectors may experience different water distribution than planar arrays.
Water Distribution and Dynamics: The uniformity of the water film, the presence of individual droplets, or the formation of rivulets play a crucial role. Surface tension, wind, and gravity influence the water distribution.
Frequency of Operation: The dielectric properties of water are strongly frequency-dependent, and higher frequencies generally experience greater attenuation due to water.
Polarization: The orientation of the electric field relative to the water distribution can influence the attenuation. Horizontal polarization is often more susceptible to attenuation from water droplets compared to vertical polarization.
Temperature: The dielectric properties of water are also temperature-dependent.

(vii) **Dependence on Rainfall Intensity**

Rainfall intensity is a primary driver of wet antenna attenuation. During light rainfall, water may form a sparse distribution of small droplets on the antenna surface. As rainfall intensity increases, these droplets can coalesce, forming a more continuous film. At very high rainfall rates, the water may form thicker films or even streams running off the antenna surface.

The relationship between rainfall intensity and wet antenna attenuation is generally non-linear. Several models have been proposed to characterize this relationship. These models can be broadly categorized into:

Empirical Models: These models are derived from experimental measurements and often take the form of power-law relationships relating attenuation to rainfall rate.
Semi-Empirical Models: These models combine theoretical considerations with empirical data to provide a more generalized approach.
Physical Models: These models attempt to simulate the electromagnetic interaction of water on the antenna surface based on physical principles. However, these are often complex and computationally intensive.

3. Methodology

3.1: Wet Antenna Attenuation Mechanisms

When rain wets an antenna radome or flattens on a horn aperture, a thin film of water (thickness t in mm) forms. This film modifies the effective reflection coefficient Γ at the air–radome and radome–water interfaces and increases absorption losses. A simplified plane-wave transmission model through a three-layer medium (air–water–radome–antireflection coating–free space) yields an excess insertion loss:

$$\mathrm{WAA} \approx 20 \log10 |(1 - \Gamma\_\mathrm{total})| \qquad (2)$$

where Γ_total accounts for multiple reflections within the water film. For film thickness $t \ll$ wavelength λ, one can approximate:

$$\Gamma \approx (\varepsilon\_w - 1)/(\varepsilon\_w + 1) - j(2\pi\, t/\lambda)(\varepsilon\_w - 1)/(\varepsilon\_w + 1)\hat{}2 \qquad (3)$$

and the dielectric constant ε_w of rainwater at microwave frequencies is modeled by Debye relaxation:

$$\varepsilon\_w(f) = \varepsilon_0 + (\varepsilon\_s - \varepsilon_0)/(1 + j\, f/f\_\mathrm{rel}) \qquad (4)$$

with $\varepsilon\_s \approx 78.4$, $\varepsilon_0 \approx 4.9$, and relaxation frequency $f\_\mathrm{rel} \approx 17$ GHz at 20 °C

3.2 Segregation of Excess Attenuation

Total attenuation (A_t) measured on a link can be expressed as:

$$A\_t = A\_r + A\_w + b \qquad (5)$$

where

A_r is the path rain attenuation, (A_w) is the wet antenna attenuation, and (b) is the baseline attenuation in clear-air conditions.

Using ITU-R models for (A_r), the excess attenuation (EA) component, (A_t - A_r - b), is attributed to wet antenna attenuation.

3.3 Data Collection

The study utilizes data from real-world microwave communication links operating in the 18–38 GHz frequency bands. Rainfall intensity data were obtained from collocated rain gauges or, alternatively, from radar-derived rainfall estimates. Link attenuation time series were sampled at one-minute intervals.The path attenuation due solely to rain (A_rain_path) was estimated using the ITU-R P.838 coefficients. The residual ΔA = A_total – A_rain_path includes WAA plus measurement noise. Dry intervals (rain rate < 0.1 mm/h) established the measurement noise floor (~0.05 dB).

4. Results and Discussion

This section shows how antenna diameter, transmision frequency and weather conditions impact antenna performance. The antenna's physical size (diameter) is primarily determined by the target wavelength for optimal performance and gain. Fig. 1 is plotted to determine the influence of weather conditions and antenna size on its link gain under clear sky and wet rain conditions. The figure shows that larger diameters typically result in higher gain and better efficiency, but does not inherently prevent the effects of a wet surface. Wet antenna performance is negatively impacted by weather conditions, as increased wet surface leads to greater signal attenuation due to the formation of water films and droplets. Particularly, for a given frequency, the figure indicates that antenna gain is directly proportional to its diameter (or effective aperture). This means that a larger antenna can focus its signal more tightly, resulting in higher gain, while a smaller antenna will have lower gain. The relationship is not strictly linear; for example, doubling the diameter of an antenna can increase its gain by a factor of approximately 5.8 in decibels, or 7.5 dB. This shows that both weather conditions and antenna size affect wet antenna performance, primarily through wet antenna attenuation (WAA) caused by the water layer that forms on the antenna surface or radome.

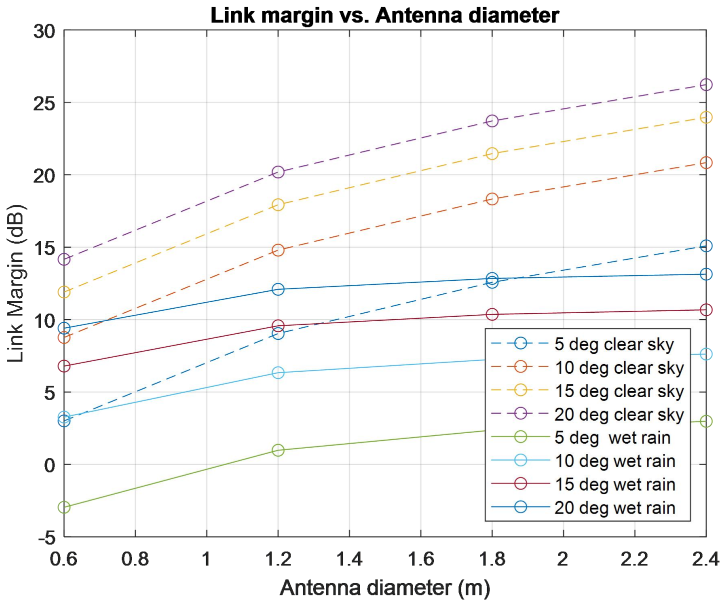

Fig. 1: Link Margin as a function of Antenna Diameter

Figs. 2 to 4 show that rain intensity directly influences the thickness and distribution of the water film on the antenna surface and the density of raindrops in the propagation path. Heavier rain leads to a thicker water film and more water in the atmosphere, resulting in greater signal attenuation loss through absorption and scattering. For short-range communication links, the weather antenna surface due to the water film on the antenna can be a more significant source of signal degradation than the attenuation from rain in the air along the path.In essence, while rain intensity dictates the severity of the weather event, the antenna's size, design, and condition ,(especially the surface's water-repellent properties, determine how effectively it can shed water and resist the resulting signal degradation. Larger antennas generally have higher gain and narrower beamwidths, making them more sensitive to pointing accuracy and any signal loss caused by the wet surface or an obstruction within the narrow beam. Accordingly, the appropriate antenna size may be quite sensitive to local weather conditions, such that locations with rainy weather conditions will require larger antennas than those with dry climates.

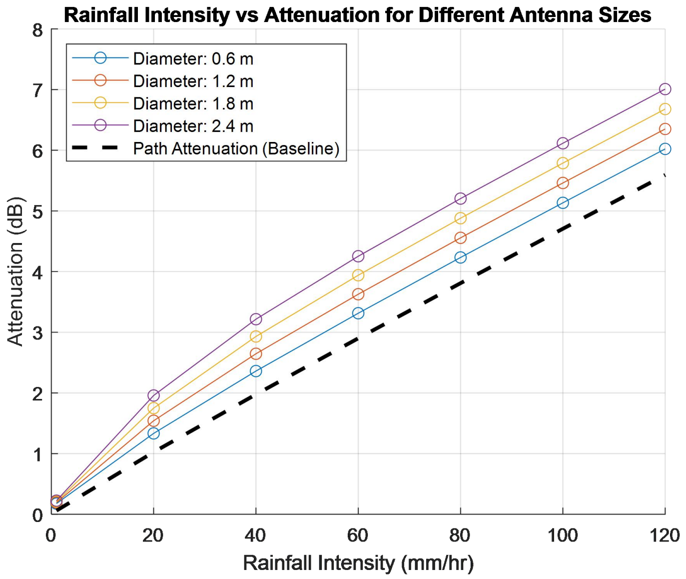

Fig. 2: Rainfall Intensity as a function of Antenna Sizes

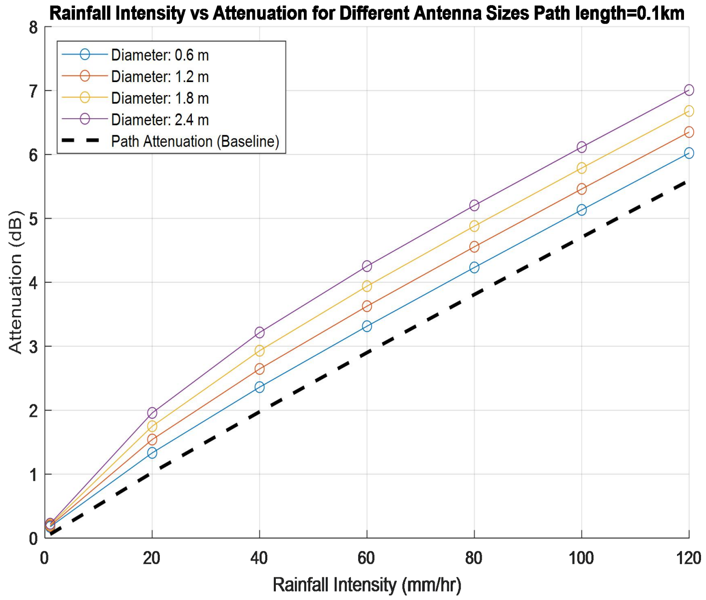

Fig. 3: Rainfall Intensity as a function of Antenna Sizes for 0.1km length

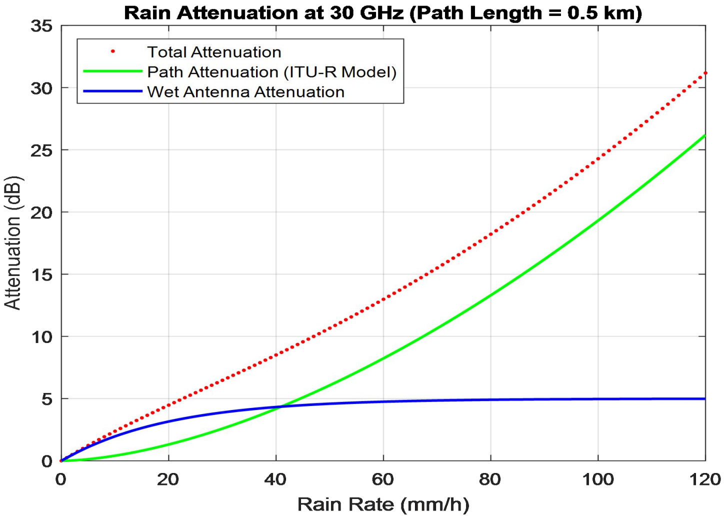

Fig. 4:Rainfall Intensity as a Rain rate for 0.5km length

As revealed in Figs. 5 and 6, while rain attenuation occurs at all frequencies, it becomes more pronounced at frequencies above 10 GHz. At frequencies below 10 GHz, highly hydrophobic (water-repellent) treatments can almost completely eliminate the water film effect. Thus, higher frequencies exhibit greater sensitivity to wet antenna attenuation due to smaller wavelength-to-droplet size ratios and higher dielectric losses.

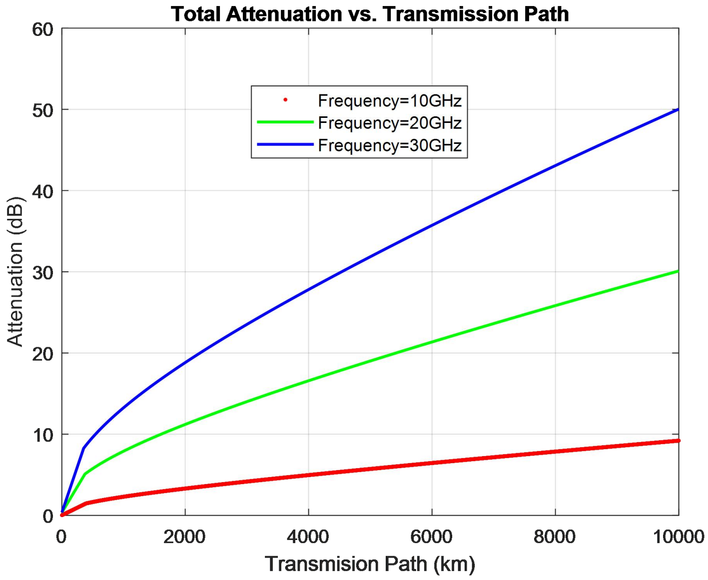

Fig .5:Total Attenuation as a function of Transmission Path with frequency

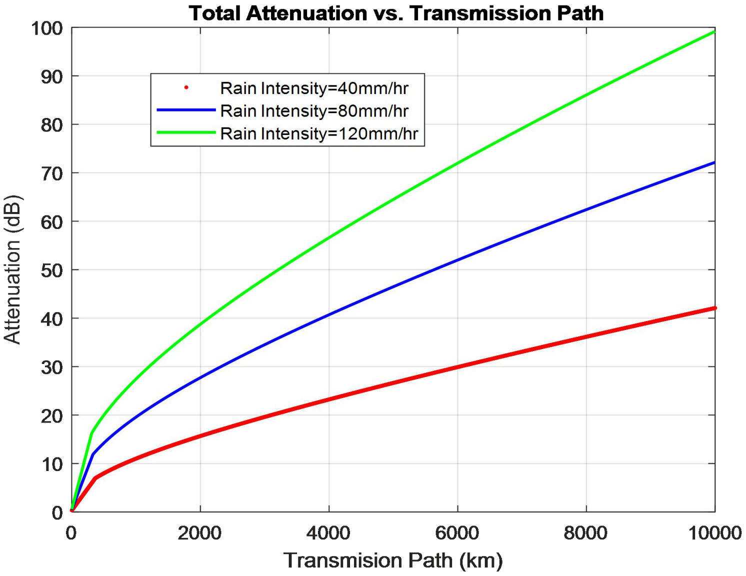

Fig. 6: Total Attenuation as a function of Transmission Path with rain rate

Results show that higher frequencies, path length and rain rates exhibit greater sensitivity to WAA due to smaller wavelength-to-droplet size ratios and higher dielectric losses. Cross-polarized links show a slightly higher WAA compared to co-polarized configurations due to changes in surface scattering characteristics. This persistence complicates the use of microwave links for instantaneous rainfall estimation without proper filtering.

5. Conclusions

Microwave communication links, particularly those operating in cellular networks, are susceptible to signal degradation caused by atmospheric conditions. Among these, rainfall presents a significant challenge, leading to attenuation of the transmitted signal. While dry antenna operation is well-understood, the presence of water on the antenna surface during rainfall, known as wet antenna attenuation, introduces a distinct and often underestimated loss mechanism. This paper presents a detailed investigation into the quantification of wet antenna attenuation on cellular microwave communication links, focusing on its dependence on rainfall intensity. First, the paper provided a comprehensive quantification framework for wet antenna attenuation as a function of rainfall intensity. Empirical evidence confirms that WAA contributes a non-negligible, nonlinear loss that must be included in high-frequency link budgets. Then, and propose a methodology for characterizing this attenuation using experimental data. The proposed models and methodologies can provide an improved predictive performance of communication systems and support the dual use of such links for meteorological sensing.

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