

Framework for Rain Attenuation in mmWave Links Validated by Ray Tracing and Real Measurements

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Abstract—Millimeter-wave (mmWave) communication systems are highly sensitive to atmospheric conditions, particularly rain attenuation, which can significantly degrade link performance over multi-kilometer distances. Although analytical attenuation models and ray-tracing tools are widely used for propagation analysis, validating rain-induced degradation using real operational links remains challenging due to incomplete link-budget information, environmental uncertainties, and the lack of path-level validation methodologies. This paper presents a path-based framework for evaluating and validating rain-induced attenuation in mmWave links using real measurements, ray tracing, and ITU-R propagation models. The proposed methodology combines received signal level (RSL) measurements from operational OpenMesh links, Wireless InSite ray-tracing simulations, and path-level rain attenuation modeling based on ITU-R recommendations. Rain attenuation is applied individually to each ray-traced propagation path before coherent recombination. The main contribution is a measurement-based validation framework that combines site-specific ray tracing, dry-weather calibration under incomplete link-budget information, and ITU-R rain modeling against operational wireless-link measurements enabling a more physically consistent representation of weather-induced degradation. The framework is evaluated using real operational links operating at approximately 68 GHz and compared against a lower-frequency 5 GHz control scenario. Experimental results demonstrate strong attenuation during precipitation events at mmWave frequencies, while the 5 GHz link exhibits significantly lower sensitivity to rainfall. The results also indicate that relative attenuation trends remain stable under moderate geometric perturbations, suggesting robustness to small deployment uncertainties. The proposed framework contributes toward scalable and physically grounded propagation modeling under weather variations, with potential applications in future weather-aware beam management, adaptive communication strategies, and AI-assisted wireless systems for mmWave and 6G networks.

I. INTRODUCTION

Millimeter-wave (mmWave) communication is a key enabling technology for next-generation wireless systems, including 5G, beyond-5G, and emerging 6G networks. The large bandwidth available at frequencies above 60 GHz enables high data rates and low-latency communication, but also increases the sensitivity of wireless links to atmospheric effects such as rain attenuation [1]. In practical deployments, particularly for backhaul, fixed wireless access, and vehicular communication systems, rain-induced attenuation can significantly degrade link performance over distances of a few kilometers [2].

Recent studies have demonstrated the strong impact of weather conditions on high-frequency propagation channels

[3], [4]. These works highlight the importance of weather-aware communication strategies and reinforce the need for accurate propagation models capable of reproducing realistic environmental effects. Such models are becoming increasingly important for the development of adaptive communication mechanisms, including AI-assisted beam management, weather-aware beam tracking, and data-driven resource allocation approaches for future mmWave and 6G systems.

At the same time, ray-tracing tools such as Wireless InSite are widely used to model site-specific propagation environments, capturing geometric effects including line-of-sight (LOS), reflections, diffraction, and multi-path propagation. Rain attenuation has also been incorporated into previous ray-tracing studies, including site-specific simulations and formulations that apply precipitation-dependent losses to individual propagation paths [5], [6]. Therefore, the contribution of this work does not rely on the path-level attenuation operation itself, but on its integration into a validation framework using reconstructed operational links and real weather-dependent RSL measurements.

Real-world datasets analyses such as OpenMesh [7] provide valuable long-term measurements of received signal level (RSL) from operational wireless links under realistic environmental conditions. These datasets enable the observation of weather-induced signal degradation directly in deployed systems. However, they often lack complete link-budget information, including transmit power, antenna gains, and hardware characteristics, making direct comparison between simulated and measured received power difficult.

This mismatch creates a fundamental validation challenge: *how to assess the correctness of propagation models under weather variations when complete system information is unavailable*. Moreover, operational wireless measurements may exhibit temporal delays, localized weather effects, and residual attenuation phenomena that are not fully captured by idealized atmospheric attenuation models. Traditional validation approaches typically rely on absolute power comparisons, which are difficult to apply under incomplete metadata and heterogeneous deployment conditions.

In this work, we address this validation problem through a framework that combines (i) operational wireless-link measurements, (ii) site-specific three-dimensional ray-tracing simulations, and (iii) ITU-R propagation models. The proposed framework applies rain attenuation to individual ray-traced propagation paths and evaluates the resulting model against operational links for which complete link-budget information

is unavailable. To this end, we employ a dry-weather calibration procedure, compare link-level scalar, coherent path-based, and incoherent path-based formulations, and evaluate the resulting relative attenuation against OpenMesh measurements. The framework is evaluated using links operating at approximately 68 GHz together with a 5 GHz control case, and its sensitivity to moderate geometric perturbations is also investigated.

A. Related Work

Weather effects on mmWave propagation have been extensively investigated due to the strong sensitivity of high-frequency wireless links to atmospheric attenuation. Several studies have demonstrated that rain, snow, fog, and other environmental conditions can significantly degrade signal quality in mmWave systems, particularly above 60 GHz [3], [4]. These works reinforce the importance of weather-aware communication mechanisms and motivate the development of accurate propagation models capable of representing realistic environmental effects.

Most existing studies focus either on analytical attenuation prediction or controlled propagation measurements. ITU-R models are widely adopted for estimating rain attenuation as a function of frequency and rainfall intensity [8], while measurement campaigns have confirmed the strong frequency dependence of atmospheric losses at mmWave bands. However, these approaches are often limited in scalability, scenario diversity, or reproducibility, which restricts their applicability to large-scale evaluation and data-driven wireless research.

Real-world datasets collected from operational wireless infrastructure provide an important complementary perspective. In particular, OpenMesh dataset analysis [7] enables long-term observation of received signal degradation under realistic environmental conditions. Nevertheless, such datasets typically lack complete link-budget information and do not provide path-level propagation analysis or ray-tracing-based validation. As a result, they are insufficient for evaluating how weather conditions affect individual propagation paths and multi-path recombination.

Simulation-driven frameworks have also enabled scalable wireless dataset generation. For example, Multimodal-Wireless [9] integrates CARLA, Blender, and Sionna to generate synchronized sensing and communication data under different environmental scenarios. However, weather is primarily represented at the scene and sensor level rather than through explicit rain attenuation of propagation paths.

Ray-tracing techniques are widely used to model geometric propagation effects such as LOS, reflections, and multi-path propagation [1]. Nevertheless, weather-induced attenuation is commonly introduced as a global scalar loss applied to the received signal, without evaluating how rainfall affects individual propagation paths or the coherent recombination of multi-path components. In this context, there is still a gap between scalable simulation-based wireless modeling and validation against real operational links under weather variations. This motivates the need for validation frameworks capable of combining real measurements, ray tracing, and

physically grounded rain attenuation models in a unified and reproducible methodology. Such frameworks are important not only for validating weather-aware propagation behavior, but also for enabling the future development of scalable datasets and adaptive communication mechanisms for mmWave and 6G systems.

II. METHODOLOGY AND EXPERIMENTAL SETUP

This section describes the real-world measurements, scenario reconstruction pipeline, ray-tracing simulations, and path-based rain attenuation modeling adopted in this work. The overall framework is illustrated in Fig. 1. To support **reproducibility**, the preprocessing **scripts** and scenario reconstruction pipeline are publicly available¹.

A. OpenMesh Links and Weather Data

The experimental analysis is based on received signal level (RSL) measurements obtained from the OpenMesh dataset [7]. OpenMesh contains 103 directional sublinks spanning the 5–6 GHz, 24 GHz, and 58–70 GHz frequency ranges. For the present analysis, two operational links operating at approximately 68 GHz were selected as the primary evaluation scenarios, since links in this frequency range are particularly susceptible to atmospheric attenuation. An additional link operating near 5 GHz is used as a control scenario to highlight the frequency dependence of rain attenuation.

The labels Link 40, Link 45, and Link 37 correspond to the original sublink identifiers in the OpenMesh dataset and are retained for reproducibility. Link 40 operates at approximately 68 GHz over a 2.5 km dominant line-of-sight (LOS) path, while Link 45 operates near 68 GHz over a 2.3 km non-line-of-sight (NLOS) path. As a lower-frequency control, Link 37 operates near 5 GHz over an approximately 3 km NLOS path. The corresponding RSL measurements were temporally aligned with rainfall observations from nearby meteorological stations.

B. Scenario Reconstruction and Ray Tracing

The evaluated scenarios were reconstructed as three-dimensional (3D) urban environments using the transmitter and receiver coordinates available in the OpenMesh metadata. The corresponding building footprints and available geometric information were extracted from OpenStreetMap (OSM) and processed using the Raymobtime framework [10], [11]. The resulting geometry was refined in Blender and exported to Wireless InSite for three-dimensional ray-tracing simulations.

The simulations were configured using the same carrier frequencies as the real links. Frequency-dependent material properties associated with asphalt, concrete, and building surfaces were adjusted according to the evaluated scenarios. Atmospheric parameters including humidity, pressure, and temperature were configured in Wireless InSite, whose atmospheric model was also used to account for gaseous attenuation, including oxygen absorption.

¹<https://raymobtime.lasseufpa.org/>

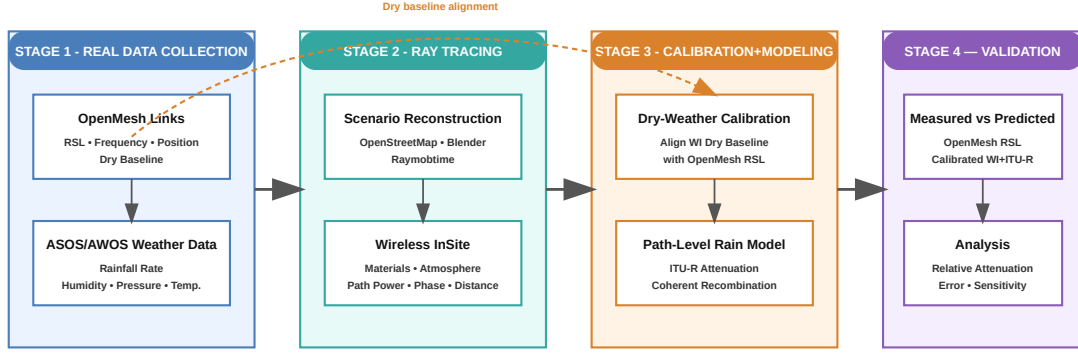


Fig. 1. Proposed framework combining real measurements, ray tracing, dry-weather calibration, and path-level rain attenuation modeling.

Wireless InSite was used to extract path-level propagation information, including received power, phase, propagation distance, and path interactions. The LOS case is dominated by the direct propagation component, whereas the NLOS case exhibits a stronger contribution from reflected paths.

C. Rain Attenuation and Path-Based Modeling

Rain attenuation is modeled according to the ITU-R P.838 recommendation [8]. For a rainfall rate R , the specific attenuation γ_R (dB/km) and the attenuation of the m -th propagation path are given by

$$\gamma_R = kR^\alpha, \quad A_m = \gamma_R d_m, \quad (1)$$

where R is the rainfall rate in mm/h, k and α are the frequency- and polarization-dependent coefficients defined by ITU-R P.838-3, d_m is the propagation distance of the m -th path in kilometers, and A_m is the corresponding rain-induced attenuation in dB.

For comparison, we define a link-level scalar baseline in which the rain-induced excess attenuation is applied once to the aggregate Tx–Rx link, consistent with conventional terrestrial rain-fade and link-budget treatments [12], [2]. The path-based implementation instead assigns the attenuation A_m according to the length of each ray-traced path before recombination.

Let M denote the number of propagation paths resolved by the ray-tracing simulation. For the m -th path, let a_m and ϕ_m denote its amplitude and phase, respectively. The dry-weather equivalent channel coefficient h , the corresponding coefficient under rain h_{rain} , and the received power P_r are modeled as

$$\begin{aligned} h &= \sum_{m=1}^M a_m e^{j\phi_m}, \\ h_{\text{rain}} &= \sum_{m=1}^M a_m 10^{-A_m/20} e^{j\phi_m}, \\ P_r &\propto |h_{\text{rain}}|^2. \end{aligned} \quad (2)$$

This formulation enables path-level analysis of weather-induced attenuation while preserving coherent recombination among propagation paths. For comparison purposes, an incoherent formulation is also evaluated by summing the attenuated path powers without phase recombination, i.e.,

$$P_r^{(\text{inc})} = \sum_{m=1}^M |a_m|^2 10^{-A_m/10}. \quad (3)$$

This formulation removes coherent phase interactions among propagation paths while still preserving path-dependent attenuation.

D. Geometric Sensitivity Analysis

To evaluate the robustness of the proposed framework under moderate geometric uncertainties, the receiver height was varied around the original deployment configuration using three settings: $(h_0 - 5)$ meter, h_0 , and $(h_0 + 5)$ m, where h_0 corresponds to the original receiver height obtained from the OpenMesh metadata.

III. RESULTS AND DISCUSSION

This section presents the experimental results obtained from OpenMesh measurements, Wireless InSite simulations, and ITU-R rain attenuation models.

A. Rain-Induced Attenuation in Real Links

Fig. 2 presents the RSL measurements and rainfall intensity for the evaluated OpenMesh links using 5-minute sampling resolution. The 68 GHz link exhibits clear attenuation during precipitation events, particularly during the intense rainfall period around January 28, where signal degradation exceeds several decibels. Smaller attenuation events are also observed during moderate rainfall periods between January 24 and January 27.

In contrast, the 5 GHz control link shows substantially smaller degradation despite experiencing the same rainfall events. Although short-term fluctuations and isolated drops are still present due to operational variability and channel dynamics, the overall attenuation associated with rainfall remains significantly lower than that observed at 68 GHz. These results confirm the strong frequency dependence of rain-induced attenuation in mmWave communication systems.

B. Calibrated Rain Attenuation Analysis

To further evaluate the consistency between simulated and real measurements, a calibrated attenuation analysis was performed using the dry-weather baseline of each evaluated link.

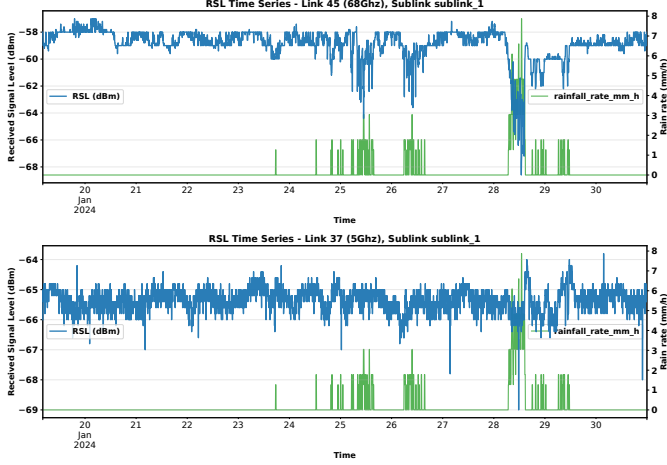


Fig. 2. RSL measurements and rainfall intensity for the evaluated 68 GHz and 5 GHz OpenMesh links using 5-minute sampling resolution.

Since OpenMesh does not provide complete link-budget information, direct comparison between absolute simulated and measured received power is not feasible. Therefore, the dry-condition Wireless InSite received power was aligned with the corresponding dry-period OpenMesh RSL using a constant calibration offset. Rain attenuation predicted by the ITU-R model was then applied according to the measured rainfall rate without additional fitting during precipitation periods.

Fig. 3 shows the measured OpenMesh RSL, the calibrated WI+ITU-R prediction, and the corresponding rainfall intensity for Link 40. The calibrated prediction reproduces the dominant attenuation trend and the overall magnitude of the strongest degradation events observed during intense rainfall periods.

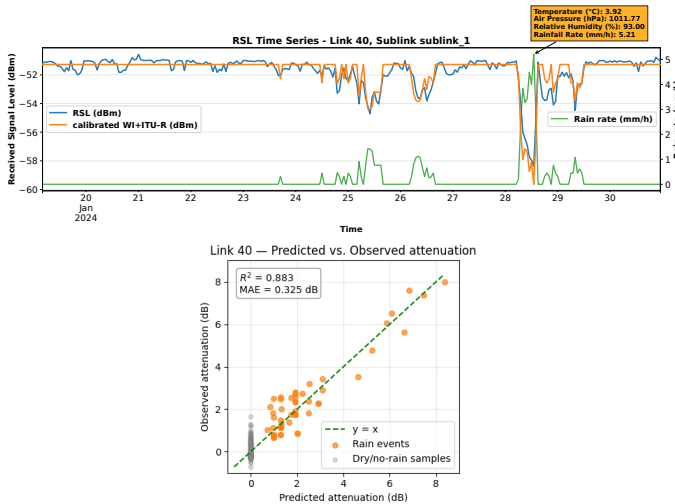


Fig. 3. Top: measured OpenMesh RSL, calibrated WI+ITU-R prediction, and rainfall intensity for Link 40. Bottom: predicted versus observed attenuation for rain events and dry/no-rain samples.

The scatter plot further compares the predicted attenuation obtained from the calibrated WI+ITU-R model against the observed attenuation extracted from the OpenMesh measurements. Rain-event samples remain close to the ideal $y = x$ reference line, resulting in an R^2 of 0.883 and a mean absolute error (MAE) of 0.325 dB. These results indicate strong consistency between the proposed framework and the measured attenuation behavior.

Although the proposed framework captures the dominant attenuation trends, some rainfall peaks do not produce equivalent RSL degradation. This behavior is expected in operational wireless deployments and may occur due to localized precipitation, temporal misalignment between weather stations and the actual propagation path, limited rainfall intensity, or natural fluctuations in the received signal level. In addition, delayed RSL recovery after intense rainfall events suggests that secondary effects such as wet radomes, wet surfaces, or residual multi-path variations may contribute to attenuation persistence even after rainfall intensity decreases.

C. Scalar and Path-Based Modeling

Fig. 4 compares conventional scalar attenuation with the proposed path-based formulation under different rainfall intensities for representative LOS and NLOS scenarios at 68 GHz.

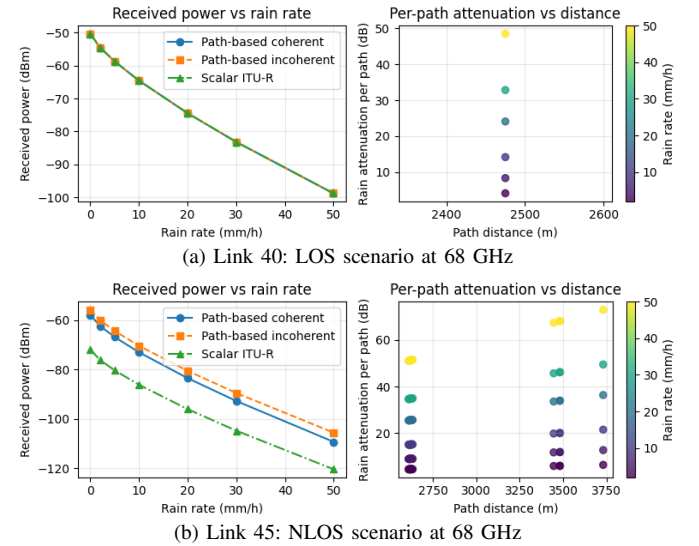


Fig. 4. Comparison between scalar, coherent path-based, and incoherent path-based rain attenuation models under different rainfall intensities.

For the LOS case (Link 40), both formulations produce similar attenuation trends since the received signal is dominated by the direct propagation path. In contrast, the NLOS scenario (Link 45) exhibits larger differences between scalar, coherent path-based, and incoherent path-based formulations due to the stronger contribution of reflected propagation paths and longer effective propagation distances.

The coherent path-based formulation applies rain attenuation individually to each propagation path before coherent recombination, whereas the incoherent formulation combines attenuated path powers without phase interaction. The larger divergence between coherent and incoherent formulations in the NLOS scenario highlights the impact of multi-path phase interactions under reflected propagation conditions.

The per-path attenuation analysis further shows that attenuation increases with both rainfall intensity and propagation distance, consistent with the ITU-R model. Unlike scalar attenuation approaches, the proposed methodology explicitly incorporates path-level propagation characteristics, providing a more physically meaningful representation of weather-induced propagation effects and a scalable framework for future weather-aware channel modeling studies.

D. Geometric Sensitivity Analysis

Fig. 5 evaluates the sensitivity of the proposed framework to receiver-height variations for the LOS Link 40. The results show that the relative rain-induced attenuation remains practically unchanged for receiver heights ranging from 20 m to 70 m, resulting in nearly overlapping attenuation curves.

This behavior is expected because the propagation-distance variation introduced by the evaluated height changes is negligible compared with the approximately 2.5 km link distance. Consequently, under dominant LOS conditions, rain-induced attenuation is primarily governed by rainfall intensity, carrier frequency, and propagation distance, indicating that the proposed framework is robust to geometric perturbations.

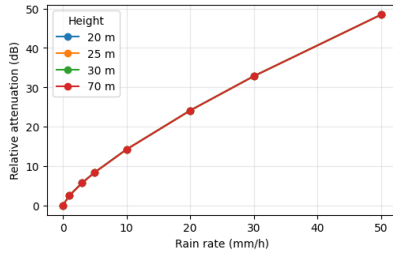


Fig. 5. Relative rain-induced attenuation for different receiver heights.

E. Discussion

The experimental results confirm the strong frequency dependence of rain-induced attenuation in wireless links. While the 68 GHz links exhibit clear degradation during precipitation events, the impact at 5 GHz remains comparatively small, consistent with ITU-R predictions. However, agreement with ITU-R P.838-3 is expected, since this recommendation provides the rain-specific attenuation model adopted in the framework. The contribution is therefore not a new rain attenuation model, but its integration with site-specific ray tracing and dry-weather calibration and its validation against real world operational mmWave measurements.

The comparison between scalar and path-based attenuation formulations shows that both approaches produce similar trends under dominant LOS conditions, since the direct path dominates the received signal. However, the proposed path-based formulation provides a more physically grounded representation by explicitly incorporating propagation-path distances and coherent recombination.

The calibrated analysis also indicates that WI+ITU-R reproduces the overall attenuation magnitude observed in real operational links, particularly during intense rainfall events. Nevertheless, some rainfall peaks do not produce equivalent RSL degradation, which may occur due to localized precipitation, temporal misalignment between weather measurements and the actual propagation path, or operational fluctuations in the communication system.

Additionally, delayed signal recovery after rainfall events suggests that secondary effects such as wet radomes, wet surfaces, or residual multi-path variations may contribute to attenuation persistence beyond the rainfall peak itself.

Finally, the results indicate that relative attenuation trends remain stable under moderate geometric perturbations, sug-

gesting that the proposed framework is robust to small uncertainties in deployment geometry.

IV. CONCLUSION AND FUTURE WORK

This paper presented a path-based framework for validating rain-induced attenuation in mmWave links using real measurements, ray tracing, and ITU-R models. Results obtained from OpenMesh links operating at approximately 68 GHz showed strong attenuation during rainfall events, while the impact at 5 GHz remained significantly smaller.

The proposed validation framework shows that an established path-based rain formulation, when combined with reconstructed ray-tracing channels and dry-weather calibration, can reproduce the main rain-induced attenuation trends observed in operational mmWave links. The results also highlight the importance of considering operational effects such as localized precipitation and wet-surface attenuation when validating weather-aware propagation models using real deployments. In addition, the analysis demonstrated robustness under moderate geometric perturbations.

Future work includes extending the framework to richer multi-path and NLOS scenarios, as well as investigating weather-aware beam management, adaptive beam tracking, and AI-assisted propagation prediction for future mmWave and 6G systems.

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