

INVESTIGATION OF ATMOSPHERIC AND WEATHER IMPACTS ON MMWAVE SIGNAL PROPAGATION

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This paper examines how weather conditions – rain, fog, and wind – affect the quality and reliability of millimeter-wave (mmWave) radio signals. Because of their short wavelength and high atmospheric absorption, these signals are highly sensitive to environmental factors, leading to attenuation, scattering, and fluctuations in received power. The study analyzes the mechanisms of signal degradation and compares different weather scenarios using propagation models and measurement data. The results emphasize the importance of adaptive modulation and weather-aware planning for stable mmWave communication, particularly in 5G/6G networks and short-range wireless systems.

Millimeter-wave (mmWave) communication in the 30–300 GHz range is an important technology for modern wireless systems, including 5G, future 6G networks, fixed wireless access, and automotive radar. These frequencies provide very wide bandwidths and enable multi-gigabit data rates, but they are highly sensitive to atmospheric conditions.

Because of their short wavelength, mmWave signals suffer stronger absorption and attenuation in the atmosphere, especially during rain, fog, snow, or high humidity. Rain can cause large signal losses, while fog and humidity add additional absorption, and wind may affect link stability in narrow-beam systems.

Rain is one of the most significant atmospheric factors affecting mmWave propagation. Rain causing attenuation due to scattering and absorption by raindrops, which are comparable in size to the wavelength of mmWave signals.

The specific attenuation γ_R (in dB/km) due to rain can be modeled using the ITU-R P.838-3 recommendation:

$$\gamma_R = kR^\alpha$$

where:

R = rain rate (mm/h),

k, α = frequency-dependent coefficients.

For example, at 60 GHz, heavy rainfall of 50 mm/h may lead to:

$$\gamma_R \approx 10 - 20 \text{ dB/km}$$

Zahid and Salous (2022) reported that short-range mmWave links (200–300 m) can experience momentary drops exceeding 15 dB during extreme rainfall, requiring robust fade margins.

Norouzian et al. (2019) extended this analysis to low-THz frequencies (100–300 GHz), demonstrating that rain attenuation increases exponentially with frequency. For instance, at 300 GHz, attenuation can exceed 30 dB/km during

heavy rainfall (50 mm/h), making link reliability a critical concern.

Fog consists of tiny water droplets (1–20 μm), which interact differently with mmWave signals compared to rain. According to Liao et al. (2023), the attenuation caused by fog increases with liquid water density and can be approximated by:

$$\gamma_{fog} = 0.2M$$

where:

M = liquid water density (g/m^3).

At frequencies of 100–300 GHz, fog can cause signal losses of about 1–3 dB/km in dense conditions. Although this is smaller than rain attenuation, it still affects highly reliable communication systems.

Atmospheric gases, especially oxygen and water vapor, also create frequency-dependent absorption. For example, oxygen absorption near 60 GHz may exceed 15 dB/km and increase with humidity. Dense advection fog can cause much greater losses than radiation fog, particularly at very high frequencies.

Wind does not directly attenuate mmWave signals but can affect communication by misaligning highly directional antennas and altering raindrop distribution, which leads to fast fading. Measurements show that storms may introduce an additional 2–5 dB loss due to changing link geometry.

Based on the reviewed literature, typical attenuation values under different weather conditions can be summarized as follows in Table 1.

Table 1. Typical mmWave Attenuation under Various Weather Conditions

Weather Condition	Frequency Range	Typical Attenuation	Source
Light Rain (10–20 mm/h)	28–60 GHz	3-7 dB/km	ITU-R P.838-3; Zahid & Salous (2022)
Heavy Rain (50–70 mm/h)	28–80 GHz	10-20 dB/km	Norouzian et al. (2019)
Dense Fog	100-300 Ghz	1-3 dB/km	Liao et al. (2023)
High Humidity	60 GHz	+15 dB/km oxygen absorption	ITU-R P.676
Wind Gusts (20–30 m/s)	Any mmWave link	2-5 dB additional loss	Mankong et al. (2023)

5G networks commonly operate in the 26–28 GHz and 39 GHz bands. Although these frequencies are less sensitive than higher mmWave bands, rain still creates challenges: it reduces cell coverage, increases outage probability and requires adaptive beamforming to maintain link quality.

For future 6G systems using sub-THz bands (100–300 GHz), weather effects become even more significant, and even short links (50–200 m) may need large fade margins. Fixed point-to-point mmWave connections are especially

vulnerable to rain attenuation, wind-induced antenna misalignment, and increased absorption from high humidity, making long-term monitoring important for predicting worst-case conditions.

Consider a 60 GHz mmWave link with a distance of 300 m during rainfall of 25 mm/h. Using ITU-R formula:

Total rain attenuation:

$$A_R = \gamma_R \cdot d = kR^\alpha \cdot 0.3 = (0.35 \cdot (25)^{0.9}) \cdot 0.3 \approx 1.86 \text{ dB}$$

Total weather-induced attenuation, including oxygen absorption (~15 dB/km):

$$A_{\text{total}} = A_R + A_{\text{oxygen}} = 1.86 + (15 \cdot 0.3) \approx 6.4 \text{ dB}$$

This example highlights that even moderate rain contributes far less attenuation than atmospheric oxygen at 60 GHz.

Atmospheric and weather conditions strongly affect mmWave and THz signal propagation. Rain is the main factor causing attenuation, which increases with frequency and rain intensity. Fog and humidity become more significant at higher frequencies, while wind can create dynamic disturbances in the communication channel. For 5G/6G networks, automotive radar, and short-range wireless links, understanding these effects is important. Techniques such as adaptive modulation, power control, beam tracking, and weather-aware planning help maintain reliable communication.

Future research should focus on real-time atmospheric monitoring, machine-learning prediction models, and improved link budgeting under changing weather conditions.

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