Computer Science and Information Technologies
Vol. 7, No. 1, March 2026, pp. 83~92
ISSN: 2722-3221, DOI: 10.11591/csit.v7i1.pp83-92

Raindrop and bit drop effects on millimeter wave network performance: a critical review

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Article Info

Article history:

Received Aug 11, 2025
Revised Dec 8, 2025
Accepted Jan 1, 2026

Keywords:

5G mmwave propagation
Adaptive modeling
Bit error and bit drop
Precipitation impact
QoS degradation
Rain attenuation

ABSTRACT

This PRISMA guided review examines how rain precipitation degrades 5G millimeter wave (mmWave) network performance, with emphasis on rain induced bit drop and its impact on end-to-end quality of service (QoS). From an initial corpus of 13,317 publications screened across IEEE Xplore, ACM Digital Library, ScienceDirect, Google Scholar, and ELICIT, 18 peer reviewed studies published between 2018 and 2024 met the inclusion criteria. Findings show that rainfall significantly weakens mmWave signals, with specific attenuation ranging from approximately 4 to 45 dB/km at 100 mm/h, particularly in tropical regions. When QoS outcomes are reported, these losses manifest as increased bit error rates, rain driven bit drop along the link, higher packet loss and delay, and reduced throughput. Key deficiencies identified include limited empirical validation of attenuation models against packet level QoS, lack of standardized propagation datasets for short range links, and weak treatment of bit level impairments within QoS analysis. To address these gaps, the review recommends enhancing ITU R P.530 and Mie scattering models with region specific measurements, implementing rain aware adaptive protocols, and adopting standardized benchmarking frameworks that link rain attenuation, bit drop, and QoS. This synthesis offers guidance for building climate aware mmWave systems and positions bit drop as a practical metric for precipitation resilience assessment.

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1. INTRODUCTION

The millimeter-wave (mmWave) spectrum, spanning 30 to 300 GHz [1]–[3], underpins 5G networks by enabling ultralow latency (~1 ms) and ultrahigh speeds (~10 Gbps) [4], [5], supporting latency-sensitive applications such as autonomous vehicles, remote surgery, and interactive gaming [6]–[8]. The global mmWave market is projected to exceed USD 13.61 billion by 2030 [9]. However, mmWave signals are highly vulnerable to precipitation, which can severely reduce signal strength and degrade performance [10], [11].

Rain attenuation arises from raindrops (1–10 mm diameter) interacting with mmWave signals (1–11 mm diameter), causing scattering and absorption losses [12], [13]. Rain rates as low as 100 mm/h can cause 4–45 dB/km signal loss, especially in tropical regions [14]–[16]. While other climatic factors affect mmWave propagation, rain is the dominant impairment [17]–[19]. However, the broader effects of precipitation on throughput, packet loss, and delay remain poorly quantified [20], and existing models underperform in complex tropical or urban deployments [21]–[24]. In this review, the term bit drop denotes the cumulative loss of useful information bits along the end-to-end path that is induced by rain-related signal degradation, manifesting through an elevated bit error rate, frame loss, packet drops, and a degraded quality of service (QoS) in throughput, delay, and reliability.

Three specific gaps motivate this study. First, there is a lack of standardized rainfall propagation datasets for short-range mmWave links, particularly for dense urban small cells. Second, attenuation and propagation models are overreliant on simulations with limited empirical validation against real traffic traces or packet-level QoS measurements. Third, few studies integrate rain attenuation, bit-level impairment, and QoS effects into a unified framework.

This study addresses these gaps through a critical literature review evaluating the impacts of precipitation on 5G mmWave performance. It offers practical recommendations. It leverages Mingers' critical framework [25], [26] to scrutinize rhetoric and objectivity and systematically identifies bias sources while stressing the need for localized predictive models [27]–[29].

2. METHOD

This study leveraged systematic literature review (SLR) methodology to identify, screen, and critically evaluate relevant peer-reviewed studies. Searches were conducted in IEEE Xplore, ACM Digital Library, ScienceDirect, and Google Scholar. The Elicit tool, Rayyan, and EndNote were used for filtering and deduplication.

2.1. Defining the research question

The research question (RQ), guided by the SLR process outlined in [27] and recent insights from [30], [31], was as follows. RQ: What are the impacts of climatic factors, particularly precipitation, on 5G mmWave network performance. In terms of QoS metrics such as throughput, packet loss, and delay?

2.2. Keywords and core concepts

Four core concepts were defined: "precipitation", "5G mmWave networks", "network performance metrics", and "impact factors". Keywords included synonyms and variants such as "5G mmWave", "precipitation", "rain attenuation", "throughput", "packet loss", "delay", and "network performance metrics".

2.3. Search string development

Keywords were combined with Boolean operators, wildcards, and controlled vocabulary. The PICO framework structured the search. The MeSH terms captured variations.

2.3.1. Database-specific adaptation

The search strings were tailored per database:

- IEEE Xplore, ACM Digital Library, Google Scholar, Elicit:
  (((((((“Impact of precipitation” OR “Influence of precipitation” OR “Effect of rain attenuation” OR “Influence of rain attenuation” OR “Impact of rain attenuation”) AND (5G OR “Fifth generation”)) AND (mmWave OR “Millimeter wave”)) AND (Network*)) AND (“Performance metrics”)) OR (Throughput)) OR (“Packet loss”)) OR (delay)
- ScienceDirect: (((((((“Impact of precipitation” OR “Influence of precipitation”) AND (5G) AND (“mmWave wave”)) AND (Network)) AND (“Performance metrics”)) OR (Throughput)) OR (“Packet loss”)) OR (delay)

2.4. Inclusion and exclusion criteria

Articles were included if they: i) were peer reviewed and published between 2018 and 2024, ii) addressed 5G mmWave performance under precipitation, iii) were in English and spanned multiple climates. Exclusion criteria: i) studies unrelated to 5G or precipitation, ii) did not meet the criteria. The PRISMA guidelines [32] and Cochrane handbook principles [33] informed this process.

2.5. Search execution and results

The primary search returned 13,317 articles. EndNote removed 983 duplicates. The titles and abstracts of the remaining 12,334 articles were further screened in Rayyan. A total of 12,175 records were further excluded. The remaining 159 articles were exported to Microsoft Excel for further screening on the basis of their introductions, methodologies, findings, and conclusions. A total of 141 articles were excluded: 119 lacked full text, 18 had overlapping data, and 4 had insufficient information. Ultimately, 18 articles met the eligibility criteria for the critical analysis. The PRISMA flow diagram is shown in Figure 1.

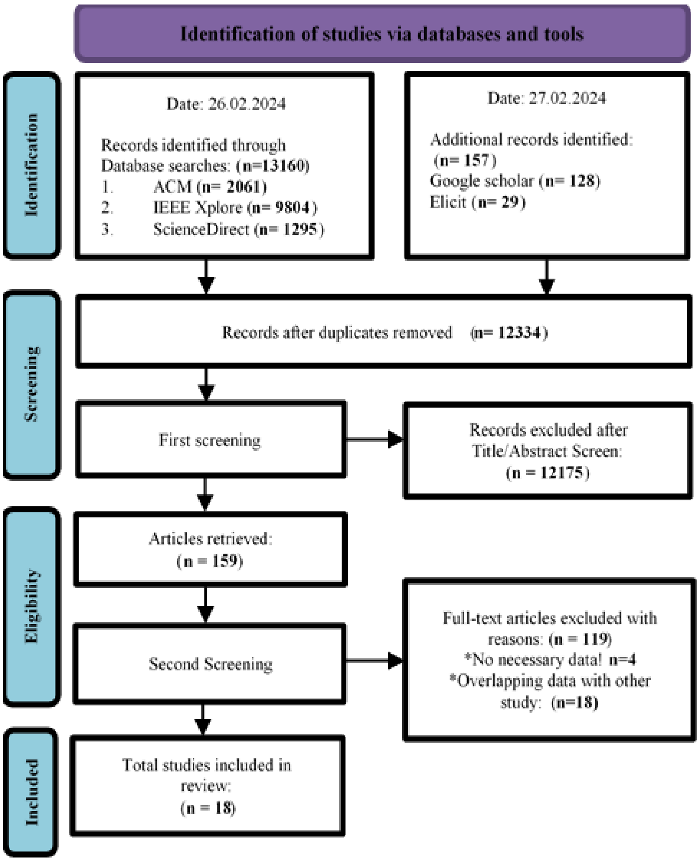


Figure 1. PRISMA flow diagram

2.6. Selection process

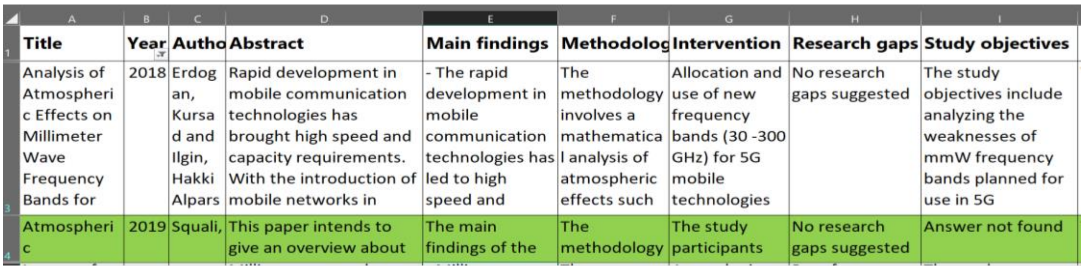
The screening involved three stages in Rayyan: i) title/abstract review, ii) introduction/conclusion review, iii) full-text and quality assessment. Eighteen studies met the methodological and geographic criteria.

2.7. Data extraction

A structured spreadsheet recorded each study's metadata, findings, methods, techniques, gaps, objectives, and geographic context, supporting synthesis, gap identification, and quality assessment. Figure 2 shows a snapshot of the screening sheet.

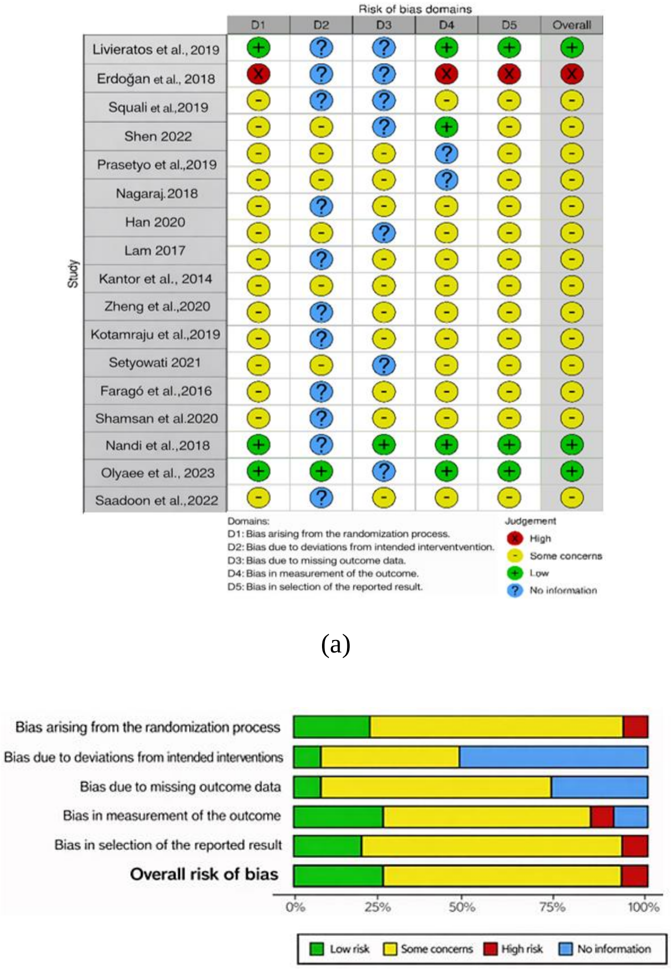
2.7.1. Risk-of-bias assessment

Bias was assessed across five domains (D1–D5) via the Cochrane RoB 2 tool [34]: D1, randomization; D2, deviations; D3, missing data; D4, outcome measurement; D5, selective reporting. Figure 3 summarizes the overall risk-of-bias assessment across the included studies. Figure 3(a) shows the traffic light plot indicating low (green), moderate (yellow), high (red), or unclear (blue) bias levels. Figure 3(b) presents the weighted overall assessment, ensuring transparency and aiding reliability evaluations. Collectively, the figure indicates that although most studies show moderate rigor, outcome measurement and selective reporting present elevated risk, affecting internal validity.



Title	Year	Autho	Abstract	Main findings	Methodolog	Intervention	Research gaps	Study objectives
Analysis of Atmospheric Effects on Millimeter Wave Frequency Bands for	2018	Erdogan, Kursad and Ilgin, Hakki Alpars	Rapid development in mobile communication technologies has brought high speed and capacity requirements. With the introduction of mobile networks in	- The rapid development in mobile communication technologies has led to high speed and	The methodology involves a mathematical analysis of atmospheric effects such	Allocation and use of new frequency bands (30 -300 GHz) for 5G mobile technologies	No research gaps suggested	The study objectives include analyzing the weaknesses of mmW frequency bands planned for use in 5G
Atmospheric	2019	Squali,	This paper intends to give an overview about	The main findings of the	The methodology	The study participants	No research gaps suggested	Answer not found

Figure 2. Snapshot of the screening spreadsheet



(a)

(b)

Figure 3. Risk of bias evaluation across included studies, showing domain-level ratings and aggregated assessment (a) traffic light plot of bias levels across five domains and (b) weighted overall ROB assessment summarizing composite bias tendencies

2.7.2. Quality assessment

The study quality, on the basis of CRD guidelines [35] and Cochrane definitions [33], was classified as high, average, or low, emphasizing validity and bias minimization [21], as shown in Table 1. The distribution shows that most studies were of average quality with only three rated high. This finding reinforces the need for more rigorous reporting frameworks and validated measurement protocols in future rain attenuation research.

Table 1. Study quality distribution

Quality category	Article count
High	3
Average	14
Low	1
Total	18

3. RESULTS AND DISCUSSION

3.1. Results

This section presents a summary of key findings from the literature analysis, with emphasis on the quality of the research, accuracy of methods, and deficiencies in the research identified.

– Synthesized findings from the literature: Eighteen (18) studies met the inclusion criteria, providing insight into the effects of precipitation on 5G mmWave throughput, packet loss, and delay, as well as methodological rigor and research gaps related to the research question. Collectively, the reviewed works confirm predictable attenuation trends across frequencies, rain rates, and climates, broadly supporting the ITU R P.530 and Mie-based formulations as first-order models. Nevertheless, many contributions remain confined to link-level metrics and rarely evaluate packet-level QoS outcomes. When QoS metrics are reported, increased attenuation is consistently associated with higher bit error rates and packet loss on the affected links, interpreted here as manifestations of rain-induced bit drop along the end-to-end path. A large proportion of studies rely on short measurement periods, single-site deployments, or simplified simulations, limiting their generalizability to dense urban 5G mmWave networks. In addition, methodological details are sometimes underreported, particularly link geometry, traffic patterns, and error control, limiting reproducibility and cross-regional comparisons.

- Addressing biases in the reviewed studies: selection and misclassification biases were common, often due to unclear rainfall classifications or unrepresentative sampling, limiting generalizability. For example, Han *et al.* [36] demonstrated strong rain-rate correlations but lacked methodological transparency, whereas Olyaee *et al.* [37] applied a robust stochastic model without real-world validation. Erdogan and Ilgin [38] addressed atmospheric effects but lacked methodological detail, highlighting the need for calibrated, region-specific models.
- Climate variability and adaptive modelling: Kantor and Bito [39] emphasized adaptive models addressing nonstationary precipitation effects on short-range mmWave links, highlighted the absence of rainfall propagation databases, particularly near 38 GHz, and called for refined models validated with localized data. Beyond attenuation modeling, adaptive modulation coding, power control, and link adaptation in response to rain fading have recently been proposed [40]. Emerging research explores machine learning-based rain prediction and scheduling correction, although these models are typically trained on limited or non mmWave datasets and rarely incorporate packet-level QoS measurements. The effectiveness of these methods for managing bit drop and QoS degradation therefore remains insufficiently validated.
- Atmospheric effects on mmWave bands: Erdogan and Ilgin [38] demonstrated that fog, rain, and gas absorption significantly impair propagation. While highlighting band allocation issues, limited methodological transparency and incomplete reporting weakened internal validity.
- MmWave backhaul attenuation: Han *et al.* [36] reported a 0.731 correlation between the rain rate and signal degradation in 32 GHz LOS-MIMO links, but the lack of methodological detail reduced replicability, although their findings reinforced weather sensitivity in backhaul links.
- Predictive modelling: Livieratos *et al.* [41] proposed an improved rain attenuation model using ITU R SG3 data, which improved the accuracy of LOS links but lacked regional variation treatment and full design detail, requiring validation across diverse climates in future work.
- Mesh network feasibility under rain events: Faragó *et al.* [42] simulated rain impacts on 5G mmWave ad hoc networks via MATLAB and suggested link alignment with the wind direction, although undocumented environmental conditions and simulation parameters limit transferability.
- Simulation of atmospheric impairments: Nagaraj [43] simulated attenuation under fog, rain, and atmospheric absorption at 10 GHz via MATLAB. While offering practical insights, unclear research gaps and design details weaken reliability.
- Low density parity check coding for mitigation: Setyowati *et al.* [44] reported that quadrature amplitude modulated (QAM) low density parity check (LDPC) coding at 60 GHz improved the BER under rain, but moderate bias of unaddressed randomization and blinding reduced internal consistency, suggesting continued code optimization and larger scale evaluation.
- Satellite link attenuation: Kotamraju and Korada [45] examined cloud-induced attenuation in satellite links above 10 GHz and recommended multisite validation to enhance model reliability, but the weak methodology limits translation to terrestrial 5G networks.
- SDS and rain modelling: Olyaee *et al.* [37] applied stochastic geometry and the Poisson point process (PPP) to assess rain and sandstorm impacts. The framework is mathematically sound but lacks field validation, reducing its external applicability.
- Region-specific rain models: Lam *et al.* [28] used three years of raindrop size distribution (DSD) data in Malaysia to improve 28- and 38-GHz predictions, surpassing ITU R baselines and highlighting the importance of local parameters; however, broader trials are needed for generalization.
- Performance in Tropical Suburbs: Prasetyo *et al.* [46] used NYUSIM simulations in Indonesia and revealed that rain-induced power losses compromised mmWave performance, although wider validation remains necessary.
- Polarization and rain attenuation: Shen [47] explored polarization effects via simulations. While minimizing the influence of polarization, incomplete design reporting limits replicability, requiring field validation.
- Cumulative atmospheric losses: Squali and Riouch [48] modeled the effects of haze, fog, vapor, and oxygen losses on mmWave propagation via advanced channel modeling, which revealed cumulative attenuation, but factor-specific impacts were not quantified, requiring broader calibration.

- Multiweather channel analysis: Khazaal *et al.* [49] modeled rain, fog, and temperature effects in Iraq via the NYUSIM and reported that rain is dominant, but geographical limitations require expansion across climates.
- Rain impact in tropical regions: Nandi and Maitra [50] confirmed that attenuation increases with frequency and distance and recommended adaptive modulation. However, the limited design transparency restricts reproducibility, despite valuable suggestions for performance optimization.
- Rain-aware network management: Han and Duan [51] quantified 1.5–4.5 dB attenuation rising to 9–19 dB from 28–73 GHz and proposed adaptive resource management strategies for rain. While methodologically sound, more regional data are needed for real-world deployment.
- Rain and diffraction model: Shamsan [29] proposed a new model that combines rain attenuation and knife edge diffraction, which enhances the understanding of combined losses in urban deployments but requires better numerical clarity and bias control.
- Commercial 5G evaluation: Zheng *et al.* [52] proposed a mmWave base station performance evaluation method, which offers field relevance, but missing scenario reporting and bias from unstructured sampling compromise reliability. Rainfall above 28 GHz degrades mmWave performance, increasing delay, packet loss, and throughput decline. Key limitations include weak empirical validation, narrow geographic scope, and methodological inconsistency. These findings reinforce the need for region-specific models, adaptive protocols, field calibrations, and advanced techniques such as LDPC, diversity combination, and rain-aware resource management.

3.2. Discussion

3.2.1. Impact of precipitation on 5G mmWave network performance

Rain substantially degrades mmWave signals, increasing packet loss, delay, and throughput decline. The attenuation ranges from 4 dB/km to 45 dB/km, with tropical regions showing greater losses, for example, 20 dB/km at 28 GHz versus 2 dB/km in temperate climates (Figure 4, Table 2). Figure 4 shows sharper frequency-dependent attenuation in tropical settings, reinforcing the need for region-specific model calibration.

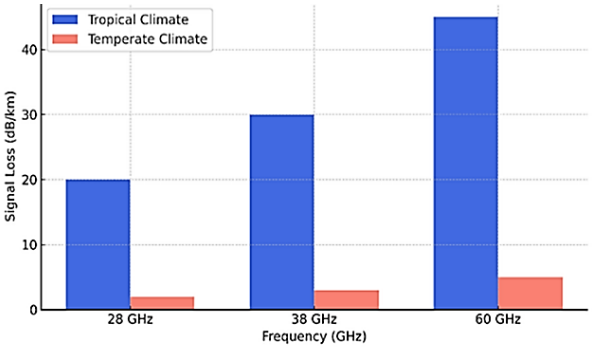


Figure 4. Comparative rain attenuation in tropical and temperate climates

Table 2. Comparative rain attenuation in tropical and temperate climates

Frequency (GHz)	Tropical loss (dB/km)	Temperate loss (dB/km)
28	20	2
38	30	3
60	45	4

Table 2 further highlights that losses at 60 GHz are approximately an order of magnitude greater in tropical regions, indicating that generic attenuation assumptions obscure climate-driven QoS risk. Most studies apply ITU-R P.530-16 and Mie scattering theory; however, these models underrepresent local climatic variability [39], [51]. A few consider fog and atmospheric absorption [43], combined haze and vapor effects [48], or broader weather losses [49]. Two gaps persist: limited quantitative QoS assessment and the lack of regional propagation datasets for short-range links. Methodological weaknesses include uncalibrated simulations [36], incomplete reporting [44], and minimal longitudinal environmental data [38]. Common themes include the following:

- Calls to refine ITU-R models for frequency-specific attenuation [41].
- Advocacy for adaptive approaches such as LDPC coding and rain-aware resource management [44], [51].
- Poor transparency in sampling, randomization, simulation settings, and environmental conditions.
- Persistent selection and misclassification biases [36], [37].

Several studies reference mitigation strategies such as adaptive modulation and coding, LDPC error control, power control, and rain-aware resource allocation, but evaluations remain largely conceptual or simulation-based. Few integrate real-time adaptation with the measured rain rate, link margin, and packet-level QoS on mmWave links, limiting assessment of their ability to prevent bit drop and performance loss during intense precipitation. This review highlights the need for experimental testbeds and field trials where adaptive coding, power control, and rain-aware scheduling are tuned directly against observed rain attenuation, bit error behavior, and QoS metrics.

3.2.2. Roadmap for empirical validation and dataset development

Enhancing rain-aware mmWave reliability requires coordinated empirical measurements, dataset creation, and protocol testing. A practical pathway begins with short-range testbeds in representative tropical and temperate locations that jointly log the rain rate, link geometry, modulation and coding parameters, and packet-level QoS across bands such as 28, 38, and 60 GHz. These measurements should be curated into an open repository that aligns attenuation traces, rain data, bit error behavior, and QoS outcomes to benchmark and calibrate the ITU R, Mie scattering, and region-specific models. The resulting dataset supports validation loops in which adaptive modulation, coding, scheduling, and prediction schemes are evaluated under measured or replayed rain scenarios via metrics such as bit drop, throughput retention, delay stability, and packet delivery reliability. This roadmap provides a concise empirical pathway for reproducible modeling, benchmarking, and adaptation in climate-aware mmWave networks.

3.2.3. Contributions of this study

This study provides a PRISMA-guided synthesis of current evidence on precipitation-induced degradation in 5G mmWave links, with the primary aim of structuring future empirical measurements, model development, and protocol design rather than introducing a new dataset or model. Gap identification: highlights the scarcity of standardized rainfall propagation datasets for short-range high-frequency links, limited QoS reporting, and weak real-world validation. Among the 18 studies, approximately two-thirds rely primarily on simulations or short-term measurements, and fewer than one-third report packet-level QoS effects. Standardization advocacy: recommends unified methodologies for reproducible attenuation prediction. Multidisciplinary integration: combines insights from climatology, telecom engineering, and signal processing. Practice guidance: advocates empirically refined models, adaptive techniques, and localized testbeds that jointly log the rain rate, link budget parameters, bit error processes, and packet-level QoS for tuning coding, power control, and rain-aware scheduling strategies.

3.2.4. Implications for research, policy, and industry

Table 3 synthesizes thematic insights and their practical significance. The gaps identified constrain the design and evaluation of adaptive mmWave protocols because the absence of standardized packet-level datasets limits the calibration of rain-aware scheduling, cross-layer optimization, and coding schemes, which are often tuned via oversimplified assumptions or nonmmWave datasets. Without empirical relationships linking rain attenuation, bit drop, and QoS, evaluating mitigation effectiveness under intense precipitation remains challenging. This study reaffirms that precipitation remains a key challenge for mmWave 5G and that closing empirical and methodological gaps is essential for climate-resilient, low-latency infrastructures.

Table 3. Thematic insights vs real-world implications

Thematic area	Summary	Strategic implication
Regional variability in attenuation	Geographic scope is narrow; higher attenuation in tropical zones (e.g., 20 dB/km at 28 GHz vs. 2 dB/km in temperate)	Expand studies to diverse climates; collect localized datasets.
Real-world Validation	Overreliance on simulations limits applicability to actual 5G deployment	Validate models with field data to ensure accuracy under real conditions.
Longitudinal data	Few longitudinal studies obscure seasonal/temporal effects on mmWave performance	Conduct multiseason monitoring to capture trends and improve predictive models.
Evaluation of mitigation techniques	Adaptive coding and rain-aware methods under tested and poorly documented.	Pilot in real deployments.
Lack of universal attenuation models	Current frameworks often mispredict in complex climates; biases remain	Standardize and refine models with diverse datasets and bias control.
Underexplored weather factors	Research focuses on rain, with sleet, snow, and fog effects on short urban links rarely studied. Even when considered, specific impacts are often not quantified.	Integrate varied weather factors into channel models; create real-time correction protocols.
Research-to-policy disconnect	Findings often not applied	Link findings to policy for infrastructure planning and foster collaboration.

4. CONCLUSION

Building on the empirical roadmap in section 3.22, this review confirms that precipitation is a dominant constraint on mmWave reliability and that structured validation, standardized datasets, and adaptive protocols are central to overcoming it. Across 18 PRISMA selected studies (2018–2024), rainfall consistently attenuates mmWave signals, reducing throughput and increasing delay and packet loss, with the strongest effects in tropical regions and higher frequencies, whereas sleet, snow, and fog remain underexplored in short-range urban links. Persistent limitations include scarce propagation datasets, weak field validation, simulation dependence, and inconsistent methodologies; consequently, models such as ITU R P.530 and Mie theory often mispredict diverse climates, underscoring the need for region-calibrated approaches. This review synthesizes current evidence and highlights critical gaps to guide empirical measurement, model refinement, and protocol design rather than proposing new models. Future work should prioritize multisite studies that build open datasets for short-range mmWave links, jointly log the rain rate, link metrics, bit errors, and packet-level QoS. Standardized benchmarking is required to compare ITU R, Mie, and calibrated variants over time under consistent bias assessment. Adaptive mitigation, including rain-aware resource management, real-time correction, LDPC-based control, and ML prediction, should be validated in live or testbed deployments via these datasets to quantify the effects on bit drop, throughput, delay, and reliability. Short-range mmWave testbeds offer a practical route for implementing these techniques and tuning link adaptation policies during rain events. Key priorities include region-calibrated models, field-validated simulations, standardized attenuation methods, longitudinal tracking, and rigorous bias control. Finally, translating research outputs into policy and infrastructure planning remains essential for resilient climate-aware mmWave networks.

FUNDING INFORMATION

No funding was involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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George Kwamena Aggrey						✓				✓	✓			
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state that they have no conflicts of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper, as no new data were created or analyzed in this study.

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