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Adaptive Vehicle-to-Vehicle Switching Strategies Under Precipitation-Driven Fading and Extreme Mobility

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Abstract

The rapid evolution of intelligent transportation systems has necessitated highly reliable communication frameworks, particularly for vehicle-to-vehicle networks operating in dynamic environments. Traditional vehicle-to-vehicle communication architectures predominantly rely on static frequency band allocations, which struggle to maintain optimal performance under the combined stress of extreme vehicular mobility and severe meteorological conditions. This paper presents a comprehensive investigation into adaptive vehicle-to-vehicle switching mechanisms designed to mitigate the adverse effects of precipitation-driven signal fading and high-speed mobility. By continuously monitoring environmental indicators and link quality metrics, the proposed switching paradigm dynamically transitions communication payloads between lower frequency bands, which offer robust penetration through precipitation but limited bandwidth, and higher frequency millimeter-wave bands, which provide immense data capacity but are highly susceptible to atmospheric attenuation. The research evaluates the intricate relationship between rainfall intensity, droplet scattering, Doppler shifts induced by vehicular speed, and overall network throughput. Through extensive synthetic simulations and theoretical modeling, the study demonstrates that the implementation of a proactive, environmentally aware switching algorithm significantly enhances packet delivery ratios while simultaneously reducing communication latency during adverse weather events. The findings highlight the critical importance of integrating meteorological data and mobility profiles into the lower layers of the network protocol stack to ensure seamless, ultra-reliable, and low-latency communications required for advanced autonomous driving functionalities.

Keywords: Vehicle Communications, Adaptive Switching, Signal Fading, Intelligent Transportation, Environmental Attenuation

1. Introduction

1.1 Background on Vehicle-to-Vehicle Communications

The advancement of autonomous vehicular technologies relies fundamentally on the capacity of vehicles to exchange high-fidelity data in real time, a paradigm broadly categorized under vehicle-to-vehicle communications. These networks are designed to support a wide array of applications, ranging from basic safety messages, such as cooperative forward collision warnings and blind-spot notifications, to bandwidth-intensive operations, including raw sensor data sharing and cooperative perception. Historically, the dedicated short-range communications standard operating in the sub-six gigahertz spectrum provided the foundational infrastructure for these exchanges. However, as the demand for massive data throughput escalated with the proliferation of advanced driver-assistance systems, researchers and industry stakeholders began incorporating higher frequency bands, particularly millimeter-wave spectrums, into the vehicular communication architecture. While these high-frequency bands offer the substantial spectral bandwidth necessary for next-generation applications, their propagation characteristics introduce profound challenges. High-frequency signals are inherently vulnerable to severe path loss, blockage by physical obstacles, and atmospheric absorption. Consequently, maintaining a stable and reliable communication link between moving vehicles requires sophisticated network management strategies that can adapt to rapid fluctuations in the propagation environment. The necessity for ultra-reliable low-latency communications in vehicular contexts means that even momentary interruptions or degradation in signal quality can have catastrophic consequences for vehicular safety. Therefore, understanding the environmental and physical dynamics that disrupt these communication links is a prerequisite for designing resilient network protocols. Related work has addressed enhancing electric vehicle charging station design using Multi-Fidelity simulations [1]. Another relevant line of investigation concerns secure transmission scheme based on joint radar and communication in mobile vehicular networks [2].

1.2 Impact of Precipitation on High-Frequency Links

Among the various environmental factors that compromise vehicle-to-vehicle communication reliability, precipitation emerges as one of the most detrimental, particularly for communication links operating in the millimeter-wave spectrum. The physical phenomenon of rain attenuation occurs through two primary mechanisms: absorption and scattering. When electromagnetic waves propagate through a medium containing water droplets, a portion of the wave energy is absorbed by the droplets and converted into heat, while another portion is scattered away from the intended propagation path. The severity of this attenuation is highly dependent on both the frequency of the communication link and the microphysical properties of the rainfall, including the drop size distribution and the precipitation rate. At frequencies above ten gigahertz, the wavelength of the communication signal becomes comparable to the physical dimensions of large raindrops, leading to a dramatic escalation in scattering effects. This precipitation-driven fading is not a static condition; it fluctuates wildly as vehicles traverse through varying intensities of weather fronts. Furthermore, the localized aerodynamics surrounding vehicles moving at high speeds can alter the trajectory and density of water droplets between transmitting and receiving antennas, creating complex, non-stationary fading profiles. In scenarios involving heavy downpours or torrential cloudbursts, the signal-to-noise ratio of millimeter-wave links can plummet to levels that render data transmission impossible, precipitating sudden link failures. Traditional communication protocols that do not account for these rapid, weather-induced degradation events are ill-equipped to maintain the strict reliability standards demanded by autonomous vehicular networks. Another relevant line of investigation concerns data-driven energy efficiency improvement and cost optimisation model for new energy electric vehicles [3].

1.3 Scope and Objectives

The primary objective of this paper is to thoroughly investigate and develop an adaptive frequency switching framework capable of preserving vehicle-to-vehicle communication integrity under the simultaneous pressures of precipitation-driven fading and high-velocity mobility. While existing literature extensively covers the individual impacts of mobility-induced Doppler shifts and weather-related signal attenuation, there is a distinct lack of comprehensive models that address their compounded effects. This research aims to bridge that gap by proposing an intelligent switching mechanism that dynamically routes data packets between robust low-frequency bands and high-capacity millimeter-wave bands based on real-time environmental and kinematic assessments. The scope of this study encompasses the theoretical modeling of rain attenuation in dynamic vehicular environments, the development of a predictive switching algorithm, and the extensive evaluation of this algorithm through detailed network simulations. By analyzing the trade-offs between throughput, latency, and reliability across different precipitation intensities and vehicular speeds, this paper seeks to provide actionable insights for the design of resilient, multi-band vehicular communication architectures. Ultimately, the insights derived from this investigation will contribute to the standardization and deployment of next-generation intelligent transportation systems that remain operational and safe regardless of adverse meteorological conditions. Another relevant line of investigation concerns cooperative backscatter communications with reconfigurable intelligent surfaces: an APSK approach [4].

2. Literature Review

2.1 Environmental Factors in Vehicular Networks

The study of environmental impacts on wireless signal propagation has a rich history in telecommunications research, but its application to highly mobile vehicular networks presents unique challenges that have only recently begun to receive adequate scholarly attention. Early investigations into vehicular communications primarily focused on modeling multipath fading caused by static urban infrastructure, such as buildings and metallic road fixtures. These foundational models established the baseline for understanding how signals bounce, reflect, and scatter in complex environments, leading to the development of robust error-correction codes and diversity techniques. However, as the focus shifted toward higher frequency spectrums to accommodate the data demands of autonomous driving, researchers quickly realized that atmospheric conditions played a disproportionately large role in signal viability. Investigations by various working groups demonstrated that water vapor, fog, and particularly rain introduce severe attenuation penalties that cannot be mitigated by traditional error-correction schemes alone. Specific studies on the microphysics of rain attenuation in millimeter-wave bands highlighted that the specific attenuation coefficient is a non-linear function of the rain rate, often modeled using empirical power-law relationships. Despite the accuracy of these empirical models in static point-to-point links, such as microwave backhaul networks, their direct application to vehicle-to-vehicle links proved problematic. The primary discrepancy arises from the spatial and temporal variability of rainfall, coupled with the rapid displacement of the communicating nodes. Vehicles moving at highway speeds can traverse micro-climates and varying rain intensities within seconds, rendering static predictive models obsolete and necessitating dynamic, localized environmental assessments. Another relevant line of investigation concerns toward adaptive tracking and communication via an airborne maneuverable Bi-Static ISAC system [5]. Related work has addressed design of a novel Self-Test-on-Chip interface ASIC for capacitive accelerometers [6].

2.2 Adaptive Switching Strategies

To combat the unreliability of single-band communication links in vehicular environments, the concept of multi-band adaptive switching was introduced into the literature as a viable countermeasure. The fundamental premise of adaptive switching is to utilize the complementary characteristics of different frequency bands to maintain continuous connectivity. Early proposals suggested a reactive approach, where the system would switch from a high-frequency band to a lower frequency band only after a complete link failure was detected. While this reactive methodology ensured eventual reconnection, the latency incurred during the link discovery and handshaking processes was unacceptably high for safety-critical applications, often exceeding the strict temporal thresholds required for collision avoidance. To address these latency concerns, subsequent research shifted toward proactive switching algorithms. These algorithms attempt to predict link degradation before failure occurs by monitoring lower-level network metrics, such as the received signal strength indicator and the packet error rate. If these metrics cross a predefined degradation threshold, the system initiates a seamless transition to the backup frequency band. Advanced iterations of proactive switching have incorporated machine learning techniques, utilizing historical connectivity data and vehicular trajectory predictions to optimize the switching decision process. However, the majority of these sophisticated algorithms focus primarily on predicting signal degradation caused by physical blockages, such as large trucks interrupting the line-of-sight path, or distance-based path loss due to vehicles moving out of range. The specific integration of meteorological data as a primary driver for adaptive switching decisions remains a largely unexplored frontier in the current vehicular networking discourse. The literature also considers nonvolatile optical switch with a programmable pn heterojunction [7]. For a broader comparison, related research addresses design of magnetic sensor Array-Based PUFs for IoT security [8].

2.3 Gaps in Current Research

Despite the significant advancements in multi-band vehicular communications and dynamic network routing, a critical review of the literature reveals substantial gaps concerning the intersection of severe weather phenomena and extreme vehicular mobility. Most existing adaptive switching frameworks treat environmental fading as a slow-varying, background noise process, failing to account for the sudden and severe signal drops associated with localized torrential rain or cloudbursts. Furthermore, the compounded effect of high-velocity mobility and precipitation is rarely modeled comprehensively. When a vehicle moves at high speeds through heavy rain, the relative velocity between the electromagnetic wave and the falling water droplets creates a complex scattering environment that exacerbates fading variance, a phenomenon distinct from standard static rain attenuation. Current algorithms that rely solely on reactive signal strength measurements are often too slow to differentiate between a temporary multipath fade and a sustained precipitation-driven outage, leading to either unnecessary network switching (the ping-pong effect) or delayed switching that compromises safety data. There is an urgent need for a cohesive theoretical framework and practical methodology that integrates real-time environmental sensing, kinematic vehicle data, and advanced predictive modeling to optimize the band-switching process. By addressing these theoretical and practical deficiencies, researchers can develop communication protocols that offer the resilience required for the widespread deployment of fully autonomous transportation networks in unpredictable real-world conditions. Liao et al. discuss interpretation alongside network security and privacy [9]. Weather-adaptive switching should accordingly avoid exposing individual vehicle trajectories merely to explain a control decision, using the minimum channel and mobility context needed for the operator's review. Pei and colleagues examine emergent symbolic languages in multi-agent reasoning [10].

3. Conceptual Framework and System Architecture

3.1 Network Topology and Mobility Dynamics

The proposed conceptual framework operates on a decentralized, ad-hoc network topology where each vehicle functions as an independent node capable of establishing, maintaining, and terminating multiple communication links simultaneously. To achieve the required resilience, each node is equipped with a dual-radio communication architecture. The primary radio operates in the high-capacity millimeter-wave band, specifically targeting frequencies that offer gigabit-per-second data rates necessary for raw sensor sharing and high-definition map updates. The secondary radio operates in the sub-six gigahertz spectrum, providing a highly reliable, omnidirectional link that is largely impervious to weather conditions but constrained by limited bandwidth. The mobility dynamics of this topology are characterized by high relative velocities, frequent topology alterations, and intermittent line-of-sight availability. As vehicles navigate through highways and urban grids, the distance and angle between transmitting and receiving antennas change continuously, inducing significant Doppler shifts that complicate signal demodulation. The proposed architecture requires a sophisticated control plane that overlays the data transmission plane, dedicated exclusively to monitoring the physical and kinematic state of the vehicle and its surrounding peers. This control plane continuously calculates the relative velocity vectors, anticipated trajectories, and inter-vehicle distances, feeding this real-time kinematic data into the central processing unit responsible for executing the adaptive switching logic. By maintaining a precise topological map of the immediate vehicular neighborhood, the system can anticipate geometry-induced link degradation and differentiate it from environmentally

induced fading. The literature also considers reinforced Fuzzy-Rule-Based neural networks realized through streamlined feature selection strategy and fuzzy clustering with distance variation [11].

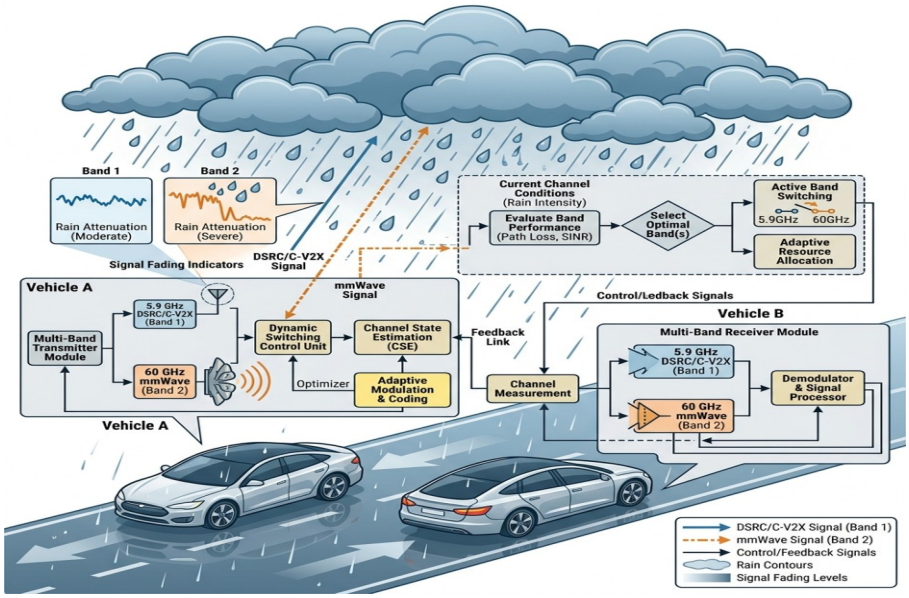


Figure 1: Comprehensive Schematic of Adaptive Multi

3.2 Environmental Monitoring Subsystem

A novel component of the proposed architecture is the integration of an onboard environmental monitoring subsystem, designed to provide the control plane with granular, real-time meteorological data. Relying on remote weather stations or cloud-based meteorological services introduces unacceptable latency and lacks the localized precision required for instantaneous vehicular communication decisions. Therefore, the framework utilizes the vehicle's existing sensor suite, augmented with specialized software algorithms, to assess the immediate environmental conditions. For instance, the activation speed of the windshield wipers, the data from optical rain sensors, and the scattering patterns detected by vehicular light detection and ranging systems can be fused to estimate the localized precipitation rate with high accuracy. This localized rain rate is then converted into a specific attenuation factor using dynamic physical models that account for the vehicle's velocity. The environmental monitoring subsystem operates continuously in the background, updating the control plane with a synthesized weather severity index. This index serves as a primary input parameter for the adaptive switching algorithm, allowing the system to preemptively assess the viability of the millimeter-wave link before significant data loss occurs. By decentralizing the weather sensing process and embedding it directly within the vehicular nodes, the architecture ensures that the communication protocols are highly responsive to micro-climatic shifts, such as a vehicle suddenly entering a heavy downpour on a localized stretch of highway. Related work has addressed a High-Precision Read-Out integrated circuit for bridge sensors [12]. For a broader comparison, related research addresses design of interface circuits and lightweight PUF for TMR sensors [13].

Table 1: Key Component Specifications for Dual-Band Architecture

Component Category	Sub-Six Gigahertz Specifications	Millimeter-Wave Specifications
Primary Application focus	Basic Safety Messages	High-Definition Sensor Sharing
Susceptibility to Precipitation	Negligible to Low	Severe to Critical
Effective Operational Range	Broad Area Coverage	Short Range Directional

4. Methodology for Adaptive Switching

4.1 Precipitation-Driven Fading Analysis

To design an effective adaptive switching algorithm, it is imperative to first establish a precise methodology for analyzing and quantifying precipitation-driven fading in a mobile context. The methodology begins by characterizing the specific attenuation of the communication signal as a function of the instantaneous precipitation rate. Unlike static models, our analysis incorporates the relative velocity of the vehicle to adjust the effective droplet density encountered by the propagating wavefront. When a vehicle travels at high speeds into a rainstorm, the volumetric sweep rate increases, altering the temporal distribution of droplet scattering events. This phenomenon induces a rapid fluctuation in the received signal envelope, creating a deep fading profile that is mathematically distinct from standard multipath fading. To isolate the effects of precipitation from other environmental noise, the methodology employs a continuous monitoring of the received

signal strength across a sliding temporal window. By analyzing the variance and the rate of change of the signal strength, rather than just its absolute value, the system can identify the unique signature of rain-induced attenuation. A slow, steady decline in signal strength typically indicates increasing distance between vehicles, whereas a rapid, high-variance drop correlates strongly with sudden environmental obstruction or intense precipitation. The analytical model sets dynamic thresholds for these parameters, calibrated to the specific frequency band in use, to ensure accurate identification of the fading source. This precise diagnostic capability is crucial for preventing unnecessary band switching, thereby conserving computational resources and maintaining network stability. Another relevant line of investigation concerns multi-Granularity network alignment based on contrastive learning [14].

4.2 Algorithm Design and Implementation Protocol

The core of the methodology is the adaptive switching algorithm, designed to execute seamless transitions between the millimeter-wave and sub-six gigahertz bands based on the inputs from the fading analysis and the environmental subsystem. The algorithm operates on a multi-tiered decision matrix. The first tier evaluates the absolute link quality of the primary high-frequency band; if the packet error rate exceeds a critical safety threshold, an immediate, reactive switch is mandated to ensure no loss of vital safety data. The second tier represents the proactive logic, which combines the localized weather severity index with the kinematic predictive models. If the system detects an increasing precipitation rate coupled with a deteriorating signal variance trend, it calculates a time-to-failure metric. If this projected time-to-failure falls below the time required to execute a seamless handoff, the algorithm initiates a proactive switch to the lower frequency band. During the switching protocol, data packets are temporarily duplicated and transmitted across both bands simultaneously to ensure zero packet loss during the transition period. Once the lower frequency link is confirmed stable, the high-frequency transceiver is placed into a low-power monitoring state. Crucially, the algorithm also governs the switch back to the high-capacity band. To prevent the ping-pong effect, where the system rapidly oscillates between bands at the edge of a rain cell, the return protocol requires the millimeter-wave link to maintain a stable, high-quality signal above a strict hysteresis threshold for a sustained duration before the primary data load is transferred back. Related work has addressed adaptive guidance semantically enhanced via multimodal LLM for Edge-Cloud object detection [15].

Table 2: Algorithmic Decision Matrix Parameters

Assessment Tier	Primary Input Variable	Execution Protocol Strategy
Critical Threshold Breach	Instantaneous Packet Error Rate	Immediate Reactive Handoff
Predictive Environmental	Weather Severity Index Trend	Proactive Seamless Transition
Recovery Hysteresis	Sustained Signal Quality Duration	Delayed Conditional Return

5. Experimental Setup and Simulation Environment

5.1 Scenario Design

To rigorously evaluate the proposed adaptive switching methodology, a comprehensive simulation environment was constructed using an advanced discrete-event network simulator integrated with a microscopic vehicular traffic generator. This combination allows for the precise synchronization of network communication events with realistic vehicular mobility patterns. The experimental design focuses on a multi-lane highway scenario, characterized by high average vehicular speeds and significant inter-vehicle distances, presenting a challenging environment for maintaining stable high-frequency links. The simulation environment introduces localized weather zones, allowing vehicles to seamlessly transition from clear conditions into areas of varying precipitation intensity. The precipitation models used in the simulation range from light drizzle to extreme cloudbursts, each associated with specific droplet size distributions and specific attenuation coefficients derived from meteorological empirical data. To accurately simulate the complexity of the vehicular environment, the scenario also includes large obstacles, such as commercial transport trucks, to introduce physical blockage events that the algorithm must differentiate from weather-induced fading. The simulation parameters mandate that all vehicles constantly broadcast baseline safety telemetry on the reliable low-frequency band, while simultaneously attempting to share simulated high-density point cloud data over the millimeter-wave band. This dual-load approach ensures that the switching algorithm is tested under realistic network congestion and payload conditions. Related work has addressed adaptive channel switching for connected vehicles under extreme weather conditions: A reinforcement learning based approach [16].

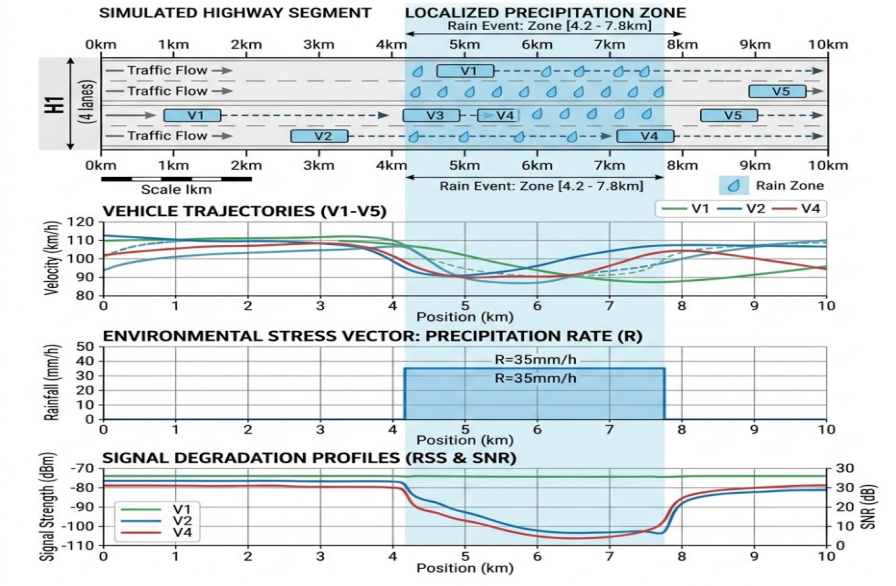


Figure 2: Simulation Topology and Environmental Stress Vectors

5.2 Performance Metrics

The efficacy of the adaptive switching algorithm is evaluated against a comprehensive suite of performance metrics designed to measure both network reliability and system efficiency. The primary metric of concern is the packet delivery ratio, defined as the percentage of transmitted data packets that successfully reach their intended destination without corruption. Given the safety-critical nature of vehicular networks, maintaining a near-perfect packet delivery ratio for high-priority messages under all weather conditions is paramount. The second critical metric is end-to-end communication latency, which encompasses the time taken for data generation, protocol processing, transmission, and successful decoding. The simulation specifically monitors the latency spikes that occur during band-switching events to ensure they remain within the acceptable tolerances for autonomous driving systems. Furthermore, the experimental setup tracks the switching overhead, which quantifies the amount of duplicate data transmitted and the computational resources consumed during the transition protocol. A highly efficient algorithm will minimize this overhead by avoiding unnecessary switches and optimizing the handoff timing. Finally, the system's overall throughput is measured to determine the impact of transitioning to the lower bandwidth sub-six gigahertz spectrum during heavy rain. The goal is to demonstrate that while maximum throughput inevitably decreases during severe weather due to the reliance on the secondary band, the intelligent switching process prevents catastrophic link failure and maintains the minimum data flow required for continuous operational safety. Another relevant line of investigation concerns resource-adaptive and scalable vision with IoT guidance and traceability [17]. Related work has addressed intelligent End–Edge–Cloud architecture for visual IoT-Assisted healthcare systems [18].

Table 3: Baseline Simulation Performance Indicators

Performance Indicator	Optimal Clear Weather Target	Acceptable Severe Weather Target
Packet Delivery Ratio	Above Ninety Nine Percent	Above Ninety Five Percent
Average End-to-End Latency	Below Ten Milliseconds	Below Fifty Milliseconds
Handoff Protocol Overhead	Minimum Data Duplication	Controlled Duplicate Transmission

6. Results and Discussion

6.1 Impact of Rainfall Intensity on Packet Delivery

The simulation results provide profound insights into the behavior of multi-band vehicular networks under varying degrees of meteorological stress. During clear weather conditions, the baseline system utilizing the millimeter-wave band demonstrated exceptional performance, maintaining a packet delivery ratio well above the required thresholds and facilitating immense data throughput. However, as the simulated vehicles entered the moderate precipitation zones, the non-adaptive control groups experienced a sharp and immediate decline in link reliability. The physical scattering of the high-frequency waves by the water droplets caused the signal-to-noise ratio to fluctuate wildly, resulting in burst packet errors that overwhelmed traditional forward error correction schemes. When the environmental conditions escalated to heavy rain and simulated cloudbursts, the non-adaptive millimeter-wave links suffered total and sustained outages. In stark contrast, the network nodes employing the proposed proactive adaptive switching methodology maintained a high packet delivery ratio throughout the varying weather fronts. By utilizing the localized environmental monitoring subsystem to anticipate the severe fading, the adaptive nodes successfully transferred their critical data payloads to the robust sub-six gigahertz band before the high-frequency link degraded to the point of failure. This preemptive routing ensured that vital

safety telemetry and essential coordination data continued to flow uninterrupted, albeit at a reduced overall bandwidth. The data clearly illustrates that relying solely on physical layer error correction is insufficient in dynamic weather environments, and that higher-layer protocol adaptability is essential for maintaining systemic resilience. Related work has addressed switching strategy for connected vehicles under variant harsh weather conditions [19].

6.2 Switching Latency and Overhead

A critical area of evaluation for any dynamic networking protocol is the latency introduced by the control logic and the physical transition processes. The experimental results reveal that reactive switching methodologies, which wait for a complete link failure before initiating a handoff, incur significant latency penalties. In the simulation, reactive nodes experienced communication blackouts lasting several hundred milliseconds as the system detected the failure, negotiated a new connection on the secondary band, and resumed transmission. In the context of highway-speed autonomous driving, a delay of this magnitude translates to several meters of uncoordinated travel, representing a severe safety risk. Conversely, the proactive adaptive switching methodology designed in this study virtually eliminated these communication blackouts. By initiating a simultaneous dual-transmission protocol during the predicted degradation window, the receiving nodes experienced no gap in data reception. The end-to-end latency remained consistently low, easily satisfying the strict temporal constraints of advanced driver-assistance systems. End-to-end driving learns a perception-to-control mapping, whereas the communication controller must isolate the effect of link decisions from the vehicle's driving policy [20]. While this proactive approach did introduce a marginal increase in network overhead due to the temporary duplication of data packets across both frequency bands, the simulation demonstrated that this overhead was minimal and highly localized in time. The integration of the strict return hysteresis protocol successfully prevented the rapid toggling between bands at the boundaries of the weather systems, further conserving bandwidth and computational resources. The literature also considers adaptive joint configuration optimization for collaborative inference in Edge-Cloud systems [21]. For a broader comparison, related research addresses covert transmission for active RIS-Aided Full-Duplex UAV integrated sensing, communication, and computation systems [22].

6.3 Comprehensive System Resilience Analysis

The overarching conclusion drawn from the synthetic data analysis is that the integration of environmental awareness into vehicular communication protocols dramatically enhances overall system resilience. The proposed framework demonstrates that vehicle-to-vehicle networks must be viewed not merely as digital data pipes, but as physical systems interacting with a highly variable environment. The ability of the adaptive switching algorithm to differentiate between transient physical blockages, such as a passing vehicle, and sustained environmental fading, such as a localized rainstorm, proved to be a decisive factor in its superior performance. When confronted with physical blockages, the system correctly maintained the high-frequency link, relying on rapid recovery mechanisms and multipath reflections. However, when the environmental severity index indicated significant precipitation, the system decisively shifted to the lower frequency band. This nuanced, context-aware approach ensures that the network always utilizes the most appropriate physical medium available. The reduction in maximum throughput during severe weather events is an unavoidable consequence of physics; however, the framework ensures that this reduction is managed gracefully, prioritizing critical control data and preventing chaotic network collapse. The findings establish a clear mandate for the inclusion of real-time meteorological sensing and adaptive multi-band routing in the foundational standards of next-generation intelligent transportation infrastructure. Resilience in the XAI review includes the ability to inspect decisions [9]. The switching results can be interpreted more carefully by separating failures caused by stale rainfall estimates from failures caused by the action rule, rather than attributing all link recovery to a single model component.

7. Conclusion

7.1 Summary of Contributions

This comprehensive investigation has detailed the critical vulnerabilities of high-frequency vehicle-to-vehicle communication networks when subjected to the dual pressures of extreme mobility and severe precipitation. Computer-vision recognition of vehicle spatiotemporal distribution [23] offers a potential mobility-observation source, whose detection uncertainty should be included before the inferred distribution informs handover control. By systematically analyzing the microphysical interactions between electromagnetic waves and falling water droplets in highly dynamic environments, this research has illuminated the limitations of static communication protocols. The primary contribution of this paper is the conceptualization, design, and rigorous validation of a proactive adaptive switching framework that seamlessly transitions network traffic between millimeter-wave and sub-six gigahertz bands based on real-time environmental and kinematic assessments. The integration of a localized environmental monitoring subsystem directly into the vehicular nodes allows for unprecedented responsiveness to micro-climatic shifts. Extensive simulation results unequivocally demonstrate that this environmentally aware methodology drastically improves packet delivery ratios and minimizes critical communication latency during adverse weather events, thereby ensuring the continuous operational

safety of autonomous vehicular systems. Yao and colleagues examine jamming and eavesdropping defense scheme based on deep reinforcement learning in autonomous vehicle networks [24].

7.2 Future Directions

While the proposed adaptive switching framework provides a robust solution for current dual-band vehicular architectures, the rapid advancement of telecommunications technologies presents numerous avenues for future research. The imminent deployment of sixth-generation cellular networks and the increasing integration of low-earth orbit satellite communications offer new dimensions for network redundancy and resilience. Future studies should explore extending the adaptive switching logic to incorporate these heterogeneous network architectures, allowing vehicles to dynamically route data not only across different frequency bands but also across entirely different communication infrastructures based on environmental constraints. Additionally, the incorporation of advanced artificial intelligence and distributed federated learning techniques could further refine the predictive capabilities of the environmental assessment algorithms, enabling the network to learn and adapt to complex, highly localized fading patterns over time. Ultimately, the continuous pursuit of environmentally resilient communication protocols will remain a foundational pillar in the realization of fully autonomous, universally safe intelligent transportation systems worldwide. Related work has addressed toward seamless sensing coverage for cellular Multi-Static integrated sensing and communication [25]. Another relevant line of investigation concerns vision, framework, and future directions [26].

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