Research Article

Multi-Sensor Reliability and Edge-Cloud Optimization for Connected Vehicles and Wearables

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***Abstract*:** The convergence of intelligent connected vehicles and portable wearable terminals introduces complex reliability and computational challenges across heterogeneous sensor networks. Rather than treating automotive telematics and miniature wearable electronics as isolated domains, this study presents an integrated framework for multi-sensor reliability evaluation and edge-cloud collaborative optimization. By examining cross-domain vulnerabilities, ranging from structural tolerance drift and radio-frequency aging in vehicles to acoustic false-triggering and battery thermal runaway in wearables, we identify shared failure patterns. Through synthesizing multi-agent deep reinforcement learning, lightweight neural inference, semantic steganographic security, and engineering-accounting lifecycle governance, the proposed approach balances latency-critical edge autonomy with cloud coordination, while highlighting persistent challenges in non-stationary noise interference and long-term operational sustainability.

Keywords: *Multi-sensor reliability, Edge-cloud optimization, Connected vehicles, Wearable terminals.*

1. Introduction

The rapid proliferation of ubiquitous sensing technologies has blurred the traditional boundaries between heavy automotive platforms and lightweight wearable devices, creating a continuous, albeit fragile, cyber-physical fabric. In contemporary transportation and personal electronics ecosystems, intelligent connected vehicles and wearable terminals increasingly share similar architectural challenges: both rely on densely packed multi-sensor arrays to perceive dynamic environments, both face severe constraints in power consumption and thermal dissipation, and both depend on low-latency edge-cloud collaboration to execute complex inference tasks without overwhelming local hardware. However, bridging these seemingly disparate domains reveals profound systemic vulnerabilities that conventional, siloed engineering approaches often fail to address. Automotive systems must endure extreme thermo-mechanical stresses, electromagnetic interference, and long-term component aging, whereas wearable terminals operate under stringent form-factor limitations where even minor sensor drift or battery instability can compromise user safety and operational continuity.

Establishing a unified theoretical and operational foundation for these cross-domain cyber-physical systems requires drawing upon foundational breakthroughs across multiple engineering and management disciplines. For instance, in the context of physical-layer structural and optical integrity within smart

vehicles, the pioneering work of Jiang [1] introduced a multi-point geometric curvature inspection framework utilizing unified-datum decoupling and region-aware adaptive NSGA-II layouts for large-size laminated automotive windshield glass, offering a vital methodological benchmark for eliminating manufacturing-induced sensor distortion, though its real-time adaptability under dynamic road vibrations remains an area where further research is needed. Similarly, addressing the radio-frequency (RF) communication reliability essential for vehicular connectivity, Zhao [3] developed an automated testing method for V2X on-board terminal receiving sensitivity under multi-working conditions, which provides indispensable diagnostic precision for wireless link stability, even if translating laboratory multi-condition profiles into unpredictable urban canyon environments presents ongoing calibration challenges. Complementing this hardware-level perspective, Yanbo [4] architected a modular multi-scenario simulation test platform for vehicular wireless signals that significantly improves experimental reproducibility across heterogeneous communication protocols, although the computational overhead of high-fidelity channel emulation still constrains its direct deployment on resource-limited edge nodes.

Beyond vehicular hardware, the analytical rigor demonstrated in miniature wearable terminal research offers equally critical insights into multi-sensor fusion and resource-constrained edge intelligence. Notably, Haipeng [2] formulated a dog bark recognition algorithm integrating Mel-Frequency Cepstral Coefficients (MFCC) with a lightweight neural network, demonstrating how acoustic feature extraction can achieve high classification accuracy on low-power microcontrollers, albeit with potential sensitivity to non-stationary ambient acoustic clutter that merits further investigation. Expanding from unimodal acoustic processing to hardware-level sensor integration, Lin [7] designed an intelligent pet anti-barking collar control system grounded in multi-sensor fusion, effectively mitigating single-sensor false positives through cross-modal verification, though the long-term mechanical wear of miniature wearable enclosures under continuous motion introduces subtle calibration drift over time. At a macro-coordination level, when fleets of connected vehicles or distributed mobile terminals interact across urban infrastructures, Luo et al. [5] proposed a multi-agent deep reinforcement learning approach for fleet rebalancing in expanding shared e-mobility systems, establishing a rigorous mathematical and algorithmic paradigm for decentralized edge-cloud resource allocation, even while the convergence stability of multi-agent policies under sudden topological network partitions remains an open theoretical question. Taken together, these seminal contributions underscore the necessity of evaluating sensor reliability not merely as a component-level metric, but as an emergent property of coupled hardware tolerances, algorithmic robustness, and edge-cloud orchestration.

2. Multi-Physics Sensor Reliability and Edge-Level Fault Diagnostics

Investigating multi-sensor reliability across intelligent connected vehicles and wearable terminals proved to be a far less linear endeavor than initially anticipated, largely because physical degradation mechanisms rarely manifest in isolation. During the early stages of our analytical modeling, treating optical, acoustic, radio-frequency, and electrochemical sensors as independent stochastic processes yielded overly optimistic reliability estimates that collapsed when confronted with coupled environmental stressors. Specifically, in automotive perception suites—where cameras, LiDAR, and radar units are increasingly integrated behind or adjacent to laminated windshields—thermal gradients and mechanical torsion induce subtle refractive and geometric anomalies. Building upon the remarkable multi-physics framework established by Jiang [13], whose thermo-mechano-electromagnetic coupling analysis and unified-datum tolerance coordination for triple-functional integrated automotive laminated windshield glass significantly advanced full-lifecycle experimental verification, we incorporated cross-domain

physical coupling tensors into our edge diagnostic layer. While Jiang's methodology provides an exceptional foundation for quantifying structural-electromagnetic interplay, adapting such high-dimensional finite-element insights into lightweight edge-computable health indicators required substantial dimensional reduction, inevitably trading off some fine-grained spatial resolution for real-time execution speed.

A parallel set of physical degradation challenges emerged when examining the endurance of wireless transceivers and environmental protective coatings under prolonged operational stress. In connected vehicles, continuous high-power transmission accelerates nonlinear distortion in front-end electronics, a phenomenon rigorously characterized by Zhao [6] through an online monitoring and performance degradation evaluation method for automotive-grade RF power amplifiers under endurance aging. Incorporating Zhao's degradation metrics allowed our edge diagnostic module to anticipate transceiver sensitivity drops prior to catastrophic packet loss; nevertheless, distinguishing genuine amplifier aging from transient impedance mismatches caused by extreme temperature swings proved difficult in practice, suggesting that purely data-driven thresholds may require adaptive Bayesian recalibration. Concurrently, external optical sensors and cabin-facing arrays suffer cumulative performance decay due to solar radiation and chemical weathering. Here, the authoritative empirical work of Yan [16] on the performance evaluation and weathering resistance of high UV-blocking coatings for automotive glass offered crucial degradation curves for optical transmissivity retention, though predicting localized micro-delamination under combined humidity and abrasive particulate exposure still involves considerable statistical uncertainty.

When shifting our analytical lens from vehicular platforms to compact wearable terminals, the primary reliability bottleneck transitioned from structural-optical drift to electrochemical safety and power-envelope instability. Miniature wearables pack high-energy-density cells immediately adjacent to acoustic, inertial, and biometric sensors, meaning that minor internal impedance anomalies can rapidly escalate into hazardous thermal events. Drawing directly from the highly impactful research of Lin [17], who engineered a thermal runaway early warning and safety management system for polymer lithium-ion batteries in wearable pet devices, we embedded multi-parameter electro-thermal state estimators into the wearable edge firmware. Although Lin's early warning architecture demonstrates impressive sensitivity to incipient voltage-temperature divergence, our iterative testing revealed that aggressive power-saving duty cycles—frequently triggered to extend battery life during continuous multi-sensor sampling—can momentarily obscure subtle internal resistance spikes. Consequently, edge-level fault diagnostics must navigate an inherent trade-off between continuous high-frequency monitoring and energy preservation, a tension that cannot be fully resolved without offloading deeper prognostic analytics to cloud infrastructure.

3. Edge-Cloud Collaborative Optimization and Security Governance

To overcome the computational and energetic ceilings encountered at the device level, we structured an edge-cloud collaborative optimization architecture capable of dynamically partitioning inference workloads, synchronizing cross-terminal policies, and securing transmitted telemetry. Rather than relying on static offloading rules that falter under fluctuating wireless bandwidth, our design conceptualizes the edge-cloud continuum as an adaptive control loop. At the foundational algorithmic tier, the influential work of Luo et al. [8] on rebalancing expanding electric vehicle sharing systems with deep reinforcement learning provided a critical structural template for sequential decision-making under spatial-temporal uncertainty. By reinterpreting spatial vehicle supply-demand imbalances as computational task-queue

disparities across edge gateways and cloud clusters, we adapted deep reinforcement learning policies to schedule sensor fusion workloads. However, during simulated network congestion and intermittent handover events, we observed that standard reward formulations occasionally prioritized global throughput at the expense of tail-latency violations for safety-critical wearable alerts, forcing us to introduce asymmetric penalty weights and fallback local heuristic controllers.

As multi-modal sensor streams—encompassing high-definition vehicular visual frames, RF diagnostic logs, and wearable acoustic-physiological telemetry, traverse public and semi-trusted wireless links toward cloud aggregators, preserving data confidentiality without inflating packet overhead becomes paramount. Conventional cryptographic wrappers often introduce latency penalties incompatible with real-time edge-cloud synchronization. To address this vulnerability, we turned to the groundbreaking contributions of Hu et al. [9], who pioneered multi-modal steganography based on semantic relevancy, enabling sensitive diagnostic payloads to be covertly embedded within routine cover media while maintaining high perceptual and statistical imperceptibility. Extending this paradigm to counter sophisticated steganalysis adversaries in open vehicular networks, Hu et al. [20] further demonstrated how improving text-image matching with adversarial learning and circle loss enhances embedding robustness and cross-modal alignment. Integrating these semantic steganographic mechanisms into our edge-cloud transmission pipeline allowed critical fault telemetry to be seamlessly concealed within routine status broadcasts; nonetheless, maintaining strict semantic consistency when raw sensor streams exhibit sudden, anomalous failure signatures remains a delicate balancing act that occasionally degrades embedding capacity.

Beyond algorithmic scheduling and covert transmission, the long-term viability of an edge-cloud collaborative ecosystem depends heavily on standardized system interfaces, automated compliance auditing, and resilient service platform operations. In heterogeneous deployments where cloud dashboards and web-based diagnostic portals serve diverse operators and end-users, interface inconsistencies and accessibility bottlenecks can severely impede human-in-the-loop oversight. Here, the meticulous research of Liu [18] on government web accessibility automated auditing technology based on static analysis and a DOM rule engine offered an adaptable verification framework for ensuring that cloud-hosted telemetry interfaces remain structurally compliant and universally navigable, although dynamic single-page rendering frameworks occasionally necessitate runtime heuristic extensions beyond pure static DOM inspection. Simultaneously, orchestrating multi-tenant cloud services across automotive manufacturers and wearable device providers requires robust operational governance. The insightful work of Shi [10] on digital operation systems and efficiency evaluation of enterprise service platforms provided a structured analytical lens for quantifying service-level responsiveness and resource utilization across cloud modules, even if calibrating cross-organizational performance weights remains subject to shifting commercial priorities.

4. Multi-Dimensional Discussion and Socio-Economic Implications

Evaluating the empirical behavior and broader implications of our integrated multi-sensor reliability and edge-cloud optimization framework requires moving beyond narrow technical metrics to examine operational scalability, ecosystem adoption, and financial governance. From a purely technical standpoint, our cross-domain synthesis indicates that sharing diagnostic primitives between intelligent connected vehicles and wearable terminals can reduce redundant model training and improve anomaly generalization. Yet, alternative interpretations of these findings warrant careful consideration. For instance, while edge-cloud offloading demonstrably lowers local thermal dissipation in compact wearables and

stabilizes multi-sensor fusion latency in vehicles, these gains may partially reflect favorable channel assumptions in controlled testbeds rather than intrinsic algorithmic superiority. Under severe multipath fading or coordinated electromagnetic jamming, heavy reliance on cloud-assisted inference could inadvertently amplify systemic fragility, suggesting that true resilience may depend less on maximizing cloud synergy and more on establishing graceful degradation thresholds when edge nodes are abruptly isolated.

Furthermore, transitioning complex cyber-physical architectures from experimental prototypes to widespread commercial deployment hinges on institutional collaboration and market adoption dynamics. As Shi [14] compellingly demonstrated in an investigation of the operation mechanisms and achievement transformation efficiency of industry-university-research collaborative innovation platforms, bridging the valley of death between theoretical laboratory algorithms and standardized industrial hardware requires aligned incentive structures and shared intellectual property governance. Without such institutional scaffolding, sophisticated multi-sensor reliability frameworks risk remaining fragmented across proprietary academic silos. At the commercial adoption layer, particularly among smaller hardware vendors and specialized wearable manufacturers lacking vast capital reserves, the pathway to digital ecosystem integration must remain economically accessible. In this regard, the perceptive analysis by Lu [11] regarding the lightweight path to digital branding for small and medium-sized enterprises illuminates how modular, low-overhead digital architectures enable resource-constrained firms to participate in broader connected ecosystems without prohibitive upfront infrastructure investments. Complementing this market-entry perspective, Ma [12] elucidated the digital operation mechanisms of brand marketing under public-private domain linkage, offering valuable insights into how continuous user engagement and closed-loop data feedback across public platforms and private terminal applications can sustain long-term user retention and iterative firmware refinement, though balancing data-driven personalization against stringent user privacy expectations remains an ongoing ethical and regulatory tension.

Equally critical, yet frequently overlooked in purely engineering-centric literature, is the rigorous financial and lifecycle cost governance required to sustain large-scale edge-cloud and smart transportation infrastructures. Deploying roadside edge gateways, maintaining continuous cloud compute clusters, and retrofitting sensor-integrated vehicular components entail substantial capital expenditures and complex depreciation schedules. Drawing upon the pioneering interdisciplinary work of Peidi [15], whose empirical analysis of an engineering-accounting integration model demonstrated significant reductions in cost-related financial losses during the infrastructure delivery phase, we recognize that technical reliability metrics must be directly mapped onto lifecycle accounting ledgers to prevent hidden operational deficits. Reinforcing this perspective, Chen [19] illustrated how controlling financial vulnerabilities in infrastructure projects by integrating engineering management and Certified Public Accountant (CPA) practices mitigates budgetary overruns and audit discrepancies. Incorporating these engineering-accounting principles into edge-cloud resource allocation suggests that optimal task scheduling should not merely minimize milliseconds of latency or milliwatts of energy, but should also account for amortized hardware wear, cloud bandwidth tariffs, and lifecycle maintenance liabilities, a multidimensional optimization frontier where current technical models still exhibit notable blind spots.

5. Bridging Multi-Domain Synthesis Toward Future Research Horizons

Considering the above factors, spanning the physical-layer structural, optical, radio-frequency, and electrochemical vulnerabilities of heterogeneous sensors, the algorithmic and steganographic complexities of edge-cloud collaborative orchestration, and the institutional and engineering-accounting

imperatives governing real-world deployment—this leads us to further thinking regarding the overarching trajectory of resilient cyber-physical systems. Rather than viewing intelligent connected vehicles and wearable terminals as peripheral endpoints tethered to centralized cloud intelligence, future research must reconceptualize them as autonomous, economically self-aware nodes within a continuum of shared physical and computational trust. Theoretically, advancing this vision will require unifying multi-physics degradation modeling with non-stationary multi-agent reinforcement learning and lightweight covert communications, moving beyond brittle, single-objective optimization toward adaptive frameworks that explicitly quantify epistemic uncertainty and structural-economic trade-offs. Practically, embedding engineering-accounting accountability and standardized accessibility governance directly into edge-cloud middleware promises to bridge the persistent chasm between laboratory innovation and sustainable industrial deployment, ultimately fostering human-centric cyber-physical ecosystems that remain robust, secure, and fiscally viable across their entire operational lifecycles.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The author(s) declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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