Modular Architecture Design of Multi-Scenario Simulation Test Platform for Vehicular Wireless Signals

Zhao Yanbo[1*]

[1] Shanghai Lixun Electronic Technology Co., Ltd., Hangzhou 310012, China
* Correspondence: Shanghai Lixun Electronic Technology Co., Ltd., Hangzhou 310012, China.

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Abstract: Vehicular wireless communication underpins vehicle interaction, vehicle-road coordination and autonomous driving, whose signal transmission performance directly affects driving safety. To solve the drawbacks of traditional vehicle wireless test platforms including tight coupling, low scenario reusability, insufficient simulation accuracy and poor multi-condition compatibility, this paper proposes a layered decoupled, dynamically reconfigurable modular multi-scenario vehicle wireless simulation test architecture. First, we analyze wireless transmission characteristics of typical driving scenarios (highway, urban, tunnel, extreme weather) and build a multi-parameter coupled channel model covering path loss, multipath fading and Doppler time-varying features. Second, six core modules (scenario scheduling, channel simulation, interference emulation, data acquisition, closed-loop control, etc.) are decoupled, with standardized interfaces developed to realize pluggable reconfiguration of scenarios, parameters and hardware. Finally, a hardware-in-the-loop platform is built for multi-scenario comparative tests. Experimental results show the architecture's average simulation error ≤3.2% and maximum error ≤4.3%. Compared with traditional platforms, scenario adaptation efficiency rises by 46.2%, hardware reuse rate increases from 38.5% to 100%, and scenario switching completes within 10 ms. It supports mainstream vehicular wireless standards (5G, V2X, UWB). This design effectively fixes the defects of conventional test systems and provides reliable engineering support for high-precision testing and algorithm iteration of 5G/6G IoV.

Keywords: intelligent connected vehicles; vehicular wireless signals; multi-scenario simulation; test platform; modular architecture; channel modeling

1. Introduction

Vehicle wireless signals are vulnerable to speed fluctuations, obstacles, traffic and weather interference, featuring rapid time variation, non-stationary fading and superimposed interference, which easily trigger bit errors, delay jitter and link disconnection. In real tests, highway communication interruption probability hits 12.7%, urban steady-state bit error rate exceeds 0.8%, and rain/snow brings 15–25 dB extra signal attenuation. High-precision, repeatable dynamic simulation testing is thus essential for vehicle communication technology iteration.

1.1 Research Background and Engineering Demand

Vehicle communication verification mainly includes real-vehicle field tests and traditional platform simulation. Field testing has uncontrollable, unrepeatable and costly scenarios: full-condition annual testing costs over 186,000 CNY, with only 57.2% test data reproducible, and extreme-condition tests carry safety risks. Traditional integrated platforms feature tightly coupled fixed modules, only supporting static single-scenario simulation with 9.7%–12.3% dynamic error (failing V2X's ≤5% precision standard). Without unified interfaces, they poorly adapt to multi-standard devices (hardware reuse rate merely 35%–40%) and require up to 72 hours per batch test, failing next-gen IoV testing demands. This paper designs a low-coupling, reconfigurable high-precision modular test architecture with prominent engineering value.

1.2 Domestic and Overseas Research Status & Gaps

Existing vehicle channel modeling and test platform research have obvious limitations in dynamic adaptation, structural decoupling and universal expansion:

1) Channel modeling: Standard 3GPP models have fixed parameters (8.2% highway error) and cannot handle composite interference; WINNER II updates parameters every 50 ms, unable to match millisecond-level vehicle channel changes; ray-tracing models suffer >30 ms delay and lack real-time closed-loop capacity. All existing models fit limited scenarios with weak dynamic performance.
2) Test platforms: Pure digital simulation has 10.5% signal distortion; traditional hardware-in-the-loop platforms have software-hardware coupling over 0.75 and need >60 ms for scenario switching; integrated physical platforms lack scalability and unified pluggable modules.

In summary, mainstream technologies have four key flaws: highly coupled structures hinder independent module iteration; only single-dimensional simulation without multi-parameter dynamic coupling; missing unified software-hardware interfaces limit multi-device compatibility; no closed-loop adjustment leads to over 8% simulation deviation.

1.3 Four Core Innovations

1) A four-layer decoupled modular architecture reduces module coupling to 0.28. Scenario, channel, interference and data acquisition modules can be independently reconfigured, greatly improving platform scalability and hardware utilization.
2) A multi-parameter coupled vehicle channel model integrates path loss, multipath delay, Doppler shift and meteorological attenuation, limiting overall simulation error within 3.2% for complex dynamic scenarios.
3) Standardized module protocols and timing synchronization (error ≤1 ms) realize plug-and-play hardware/software, fully compatible with 5G, V2X and UWB vehicle communication equipment.
4) A closed-loop dynamic testing system adjusts simulation parameters via real-time data feedback, enabling automatic, accurate, repeatable multi-scenario testing and lifting batch testing efficiency by 46.2%.

2. Modeling of Multi-Scenario Transmission Characteristics and Testing Requirements for Vehicular Wireless Systems

Transmission characteristics of vehicular wireless signals vary significantly with driving scenarios, environmental interferences and motion states. Accurate quantification of channel characteristics in various scenarios and clarification of quantifiable platform design indicators lay the theoretical foundation and prerequisite for modular architecture design.

2.1 Classification of Typical Vehicular Scenarios and Quantitative Analysis of Signal Characteristics

Combined with the national standard GB/T 39222-2020 for vehicular communication testing specifications and real driving working conditions (Zhang Y & Wang X., 2023), vehicular wireless transmission scenarios are divided into six typical categories with well-defined speed ranges, loss ranges and interference intensities for each scenario. Distinct differences exist in signal transmission characteristics across scenarios, as summarized in Table 1.

Table 1. Quantitative characteristic comparison of typical vehicular wireless communication scenarios

Scenario Type	Vehicle Speed Range	Core Channel Characteristics	Signal Fading Characteristics	Typical Loss Range
High-Speed Driving	80–120 km/h	High Doppler shift (0–350 Hz), fast time-varying channels	Fast Rician fading	65–85 dB
Urban Downtown	20–60 km/h	Dense multipath, delay spread of 50–200 ns	Rayleigh fading dominant	70–90 dB
Closed Tunnel	40–80 km/h	Superimposed signal reflections, prominent standing wave effects	Severe shadow fading	85–105 dB
Suburban Open Area	60–100 km/h	Path loss dominated, weak multipath components	Slow fading dominant	55–75 dB
Extreme Meteorological Conditions	0–60 km/h	Aggravated signal attenuation, SNR drop of 8–15 dB	Hybrid fading	80–110 dB
Congested Traffic Flow	0–30 km/h	Dense adjacent channel interference, crowded channels	Sudden deep fading	75–95 dB

2.2 Core Parameter Modeling of Vehicular Wireless Channels

To accurately characterize dynamic vehicular transmission characteristics, an integrated mathematical channel model covering path loss, multipath delay and Doppler shift is established. Model corrections are performed with quantitative parameters of each scenario to adapt to differentiated features of various working conditions.

2.2.1 Dynamic Path Loss Model

Considering the time-varying distance characteristics of vehicular scenarios and differentiated loss rules across scenarios, a dynamic path loss calculation formula is constructed:

$$PL(d)=PL(d_0)+10\alpha\lg\left(\frac{d}{d_0}\right)+X_\sigma$$

Where: $PL(d_0)$ denotes the path loss at the reference distance d_0=1m in dB; α represents the path loss exponent (2.2–2.6 for high-speed scenarios, 2.8–3.5 for urban scenarios, 3.8–4.2 for tunnel scenarios); d stands for real-time vehicle distance ranging from 5 m to 500 m in meters; X_σ is the Gaussian random shadow fading margin in dB with a value range of 3–8 dB. This model dynamically modifies the loss exponent according to different scenarios to precisely fit loss characteristics of diverse road conditions.

2.2.2 High-Speed Doppler Shift Model

Frequency shift induced by high-speed vehicle movement constitutes the core factor of channel time variation in vehicular systems. The instantaneous Doppler shift formula is expressed as:

$$f_d = \frac{v}{\lambda}\cos\theta(t)$$

Where: v denotes vehicle driving speed (0–120 km/h), λ represents signal wavelength, and $\theta(t)$ refers to the real-time angle between transmitted and received signals (0–180°). Under the extreme speed of 120 km/h, the maximum Doppler shift of the model reaches 350 Hz, which fully matches measured data of real vehicular channels and accurately reproduces fast-varying channel characteristics in high-speed scenarios.

2.3 Quantifiable Design Requirements and Technical Indicators of the Platform

Combining scenario characteristics and engineering testing pain points, quantifiable and implementable design indicators of the modular platform are clarified from three dimensions: functionality, performance and architecture. The core quantifiable indicators are listed as follows.

- **Functional Indicators**: Support dynamic reconstruction of six full-coverage typical vehicular scenarios; compatible with multi-standard signal simulation of 5G (3.5 GHz), V2X (5.8 GHz) and UWB (6–9 GHz); support customizable superposition of multi-level environmental interference (0–30 dB) and artificial interference (0–25 dB); enable fully automated data collection and analysis of 12 core parameters including bit error rate, transmission delay and signal-to-noise ratio.
- **Performance Indicators**: Overall average signal simulation error ≤3.2%, maximum single-scenario error ≤4.5%; dynamic scenario switching delay ≤10 ms; 100% module interface compatibility; data acquisition precision ≥99.2%; continuous stable equipment operation duration ≥200 hours without stalling or data loss.
- **Architectural Indicators**: Module coupling degree lower than 0.3 (industrial standard for low coupling); hardware reuse rate ≥60%; scenario expansion and function iteration without modification of underlying architecture; support on-demand addition, removal and replacement of functional modules to adapt to subsequent function upgrades.

3. Overall Modular Architecture Design of the Platform

Discarding the conventional integrated fixed architecture, this paper adopts a design philosophy of hierarchical decoupling, independent layers and closed-loop linkage to construct a four-layer modular overall architecture. From top to bottom, the layers are the scenario scheduling layer, signal and channel simulation layer, hardware interactive adaptation layer and data closed-loop control layer. Each layer operates independently with standardized interfaces to support separate iteration and reconstruction.

3.1 Core Design Principles of the Architecture

- **Hierarchical Decoupling Principle**: Each functional module is independently encapsulated, with data interaction between layers realized exclusively through standardized interfaces without underlying code or hardware binding. The module coupling degree is reduced to 0.28, completely resolving the high-coupling problem of traditional platforms.
- **Dynamic Reconfigurable Principle**: Scenario parameters, channel models, interference intensities and hardware devices can be configured and replaced on demand,

supporting rapid switching testing of multiple working conditions within milliseconds.

- **Software-Hardware Collaborative Closed-Loop Principle**: Combining the high precision **of** digital simulation and authenticity of hardware measurement, simulation parameters are dynamically corrected via data feedback, achieving over 68% improvement in simulation precision after iterative optimization.
- **General Compatibility Principle**: Unified data interaction formats, communication protocols and time sequence synchronization standards (time sequence error ≤1 ms) are formulated to adapt to multi-brand and multi-standard vehicular test equipment.

3.2 Four-Layer Modular Overall Architecture

3.2.1 Scenario Modeling and Scheduling Layer

As the top core control unit of the platform, this layer embeds six standardized scenario templates, supporting continuous adjustable vehicle speed from 0 to 120 km/h, gradient configuration of meteorological attenuation ranging from 0 to 25 dB, and customizable traffic flow interference density from 0 to 100%. Time sequence arrangement of multiple scenarios is supported, enabling presetting of more than 20 groups of continuous testing working conditions to provide high-precision time-varying scenario inputs for lower simulation units.

3.2.2 Signal and Channel Simulation Layer

Serving as the core algorithm layer of the platform, it consists of three sub-modules: multi-standard signal generation, dynamic channel fitting and multi-source interference emulation. It updates path loss, multipath delay and Doppler shift parameters in real time to support dynamic simulation of frequency shifts from 0 to 350 Hz (Li M & Zhang H., 2022), and can superimpose six types of interference signals including additive white Gaussian noise, co-channel interference and adjacent channel interference to realize high-precision simulation of complex electromagnetic environments.

3.2.3 Hardware Signal Interaction Layer

Acting as a physical adaptation transfer layer, it undertakes bidirectional conversion between digital signals and physical radio frequency signals with a bandwidth coverage of 3–10 GHz, fully matching mainstream vehicular wireless standards. All types of hardware devices are connected through standardized universal interfaces to realize plug-and-play hardware, cutting equipment adaptation time from the traditional 30 minutes to within 2 minutes.

3.2.4 Data Processing and Closed-Loop Control Layer

As the core of platform feedback optimization, it supports high-speed synchronous data acquisition at 1 GS/s, compares simulation data with measured reference data in real time, and completes a single parameter correction cycle within 20 ms to realize adaptive dynamic optimization of simulation precision.

3.3 Overall Operation Flow of the Platform

The complete operating flow of the platform is described as follows: First, test scenarios, speed working conditions and interference parameters are initialized and accurately configured in the scenario scheduling layer. Subsequently, the simulation layer completes channel modeling and wireless signal generation according to scenario parameters. Digital signals are converted into physical radio frequency signals via the hardware interaction layer and accessed to the tested vehicular equipment. The data layer collects 12 core indicators including communication bit error rate, transmission delay, signal-to-noise ratio and signal power in real time. Finally, the closed-loop feedback mechanism dynamically optimizes simulation parameters to complete automated iterative testing across multiple scenarios. The entire process maintains a time sequence synchronization error ≤1 ms with stable module linkage and lossless data communication, realizing fully automatic simulation testing without manual intervention.

3.4 Comparative Analysis of Architectural Performance Advantages

Quantitative comparisons between the proposed modular architecture and conventional integrated architecture are presented in Table 2 to intuitively reflect the advancement and engineering merits of the proposed architecture.

Table 2. Quantitative performance comparison results of architectures

Performance Indicator	Conventional Integrated Architecture	Proposed Modular Architecture	Performance Improvement Range
Module Coupling Degree	0.81 (High Coupling)	0.28 (Low Coupling)	Coupling Degree Reduced by 65.4%
Scenario Switching Delay	80–120 ms	≤10 ms	Response Speed Improved by 87.5%
Hardware Reuse Rate	38.5%	100% (Pluggable Adaptation)	Reuse Rate Increased by 61.5%
Multi-Scenario Coverage Capacity	Single Static Scenario	6 Full Dynamic Composite Scenarios	Scenario Coverage Expanded by 500%
Average Simulation Error	8.5%–12.3%	≤3.2%	Simulation Error Reduced by 62.4%
Single-Batch Testing Duration	72 h	38.8 h	Testing Efficiency Improved by 46.2%

4. Detailed Design and Modeling of Core Functional Modules

Based on the overall layered architecture, refined structural design, parameter modeling and standardized interface definition are implemented for six core functional modules, with clear definition of core performance thresholds for each module to guarantee independent functionality, controllable performance and stable linkage of all modules.

4.1 Multi-Scenario Dynamic Modeling and Scheduling Module

The core function of this module lies in parametric precise modeling and dynamic time sequence scheduling of vehicular scenarios, constructing a four-dimensional quantitative parameter library: vehicle speed parameters (0–120 km/h with continuous 1 km/h stepping), road shielding parameters (0–100% shielding density), meteorological parameters (sunny, rainy, foggy, sand-dust conditions with gradient adjustable attenuation of 0–25 dB), and traffic flow interference parameters (0–100 vehicles per kilometer flow density). A third-order smooth switching algorithm is designed for dynamic working conditions such as vehicle acceleration/deceleration, lane changing and tunnel entry/exit, limiting parameter switching fluctuation error to ≤0.5% to completely avoid simulation distortion caused by abrupt parameter changes. Meanwhile, more than 20 groups of test sequences can be preset to realize unattended automated traversal testing of continuous scenarios with a scenario scheduling accuracy of 99.8%.

4.2 Multi-Standard Vehicular Wireless Signal Simulation Module

Embedded with a high-precision signal modulation unit supporting multiple standards, this module precisely covers mainstream vehicular wireless standards including 5G (3.5 GHz), LTE-V2X (5.8 GHz) and UWB (6.5–8 GHz). The signal bandwidth supports adaptive configuration from 10 MHz to 100 MHz (Gammaa A., 2025), with adjustable transmit power ranging from -50 dBm to 20 dBm, and mainstream modulation schemes including QPSK, 16QAM and 64QAM are supported. Combined with the aforementioned Doppler shift model, the module tracks speed variations in real time and updates time-varying signal characteristics within milliseconds, achieving a frequency shift simulation error ≤2.1% under the high-speed working condition of 120 km/h. It accurately reproduces signal distortion and frequency offset characteristics in high-speed moving scenarios to ensure high consistency between simulated signals and real vehicular signals.

4.3 Dynamic Channel and Multi-Interference Simulation Module

Based on an improved ray-tracing algorithm, the iterative calculation logic of multipath signal superposition is optimized to compress single-frame calculation time within 8 ms, raising the multipath signal fitting degree above 97%. A standardized six-level interference signal library is established to support on-demand superposition of six types of signals: additive white Gaussian noise, co-channel interference, adjacent channel interference, pulse interference, meteorological interference and traffic flow interference. Interference intensity can be continuously adjusted from 0 to 30 dB with customizable interference intervals ranging from 1 ms to 10 s, which can precisely simulate extreme vehicular working conditions with dense traffic flows and complex electromagnetic environments. Measured results show that the interference superposition precision of this module reaches 98.5%, capable of fully reproducing real road electromagnetic interference environments.

4.4 Standardized Interface Adaptation Module

To address poor adaptability and low compatibility of conventional platforms, unified software and hardware interactive interface protocols are formulated in this paper, defining standardized data frame formats, 1 ms-level time sequence synchronization rules and general equipment communication protocols. All functional modules are encapsulated with unified interfaces delivering a transmission rate of 1 Gbps and a time sequence synchronization error ≤1 ms to realize plug-and-play equipment. No reconstruction of the underlying system architecture is required for newly added test equipment or scenario models, cutting equipment adaptation time from 30 minutes to 2 minutes and substantially boosting platform scalability and universality.

4.5 High-Precision Data Acquisition and Analysis Module

Adopting a high-speed synchronous acquisition architecture with a maximum sampling rate of 1 GS/s, this module supports synchronous collection of 12 core parameters such as signal-to-noise ratio, bit error rate, transmission delay, signal attenuation and frequency offset deviation, with a single-parameter acquisition precision of 99.2%. Built-in algorithms including wavelet denoising, 3σ outlier elimination and polynomial fitting analysis can automatically generate quantitative test reports and intelligently evaluate communication performance. Real-time data visualization is also supported to intuitively present millisecond-level signal fluctuation laws under various scenarios, providing precise data support for performance analysis.

4.6 Closed-Loop Automatic Control Module

Closed-loop control constitutes one of the core advantages of the proposed architecture. This module compares simulation data with real-vehicle measured reference data in real time to accurately calculate simulation errors, and dynamically corrects core parameters including channel loss, interference intensity and multipath delay based on a gradient descent optimization algorithm with a single parameter iterative correction cycle ≤20 ms (Khan A A, Laghari A A, Shafiq M, et al., 2024). After 3–5 iterations of optimization, the simulation error can be stably controlled within 3.2%, thoroughly resolving the engineering pain points of fixed static parameters and excessive errors of traditional simulation platforms.

5. System Integration and Experimental Verification

To verify the functional integrity, performance stability and scenario adaptability of the proposed modular architecture, a hardware-in-the-loop joint simulation test platform is constructed, and multiple groups of comparative experiments are designed to conduct quantitative verification from three dimensions: module performance, scenario precision and architectural efficiency. Each group of experiments is repeated five times and averaged to guarantee data reliability and reproducibility.

5.1 Construction of Experimental Platform

Experimental hardware devices include Keysight N9310A vector signal generator, SP6000 multi-channel channel simulator, high-speed PCIe data acquisition card, vehicular V2X terminal, industrial personal computer and high-precision regulated power supply. Hardware operating parameters cover signal frequencies of 3–10 GHz, channel simulation bandwidth of 100 MHz and data sampling rate of 1 GS/s. The software system consists of self-developed scenario modeling programs, channel simulation control programs, data acquisition analysis programs and closed-loop regulation programs. All devices are integrated based on standardized interfaces to realize millisecond-level collaborative linkage testing of software and hardware.

5.2 Experimental Evaluation Indicators and Scheme Design

Five core quantitative evaluation indicators are set in this paper: signal simulation precision, scenario switching efficiency, module compatibility stability, testing efficiency and hardware reuse rate. Conventional integrated fixed test platforms are taken as the control group, while the proposed modular platform serves as the experimental group. Four typical extreme vehicular scenarios are selected for comparative testing: high-speed driving (100 km/h), urban congestion (40 km/h), tunnels and heavy rain meteorological conditions. Each group of experiments is repeated five times, and abnormal data are eliminated before averaging to ensure experimental rigor.

5.3 Single-Module Performance Test Results

Independent testing results of single modules demonstrate stable operation of all functional modules without data stalling, time sequence disorder or interface mismatching. Parameter configuration error of the scenario modeling module is lower than 2.1%; multipath fitting degree of the channel simulation module exceeds 97.0%; interference superposition precision of the interference emulation module reaches 98.5%; data acquisition precision of the data collection module is 99.2%; parameter correction response delay of the closed-loop regulation module is ≤20 ms (Ornelas-Aguirre A, Rodriguez-Colina E, Pascoe-Chalke R, et al., 2023). All single-module performance indicators meet the preset design thresholds, providing reliable support for stable overall system operation.

5.4 Multi-Scenario Overall Simulation Precision Verification

High-precision comparisons are conducted between platform simulation data and real-vehicle field measured reference data, and statistical simulation errors of four core scenarios are listed in Table 3.

Table 3. Quantitative test results of multi-scenario simulation precision

Test Scenario	Average Simulation Error	Maximum Instantaneous Error	Data Fitting Degree	Error of Conventional Platform
High-Speed Scenario (100 km/h)	2.8%	3.5%	97.2%	9.1%
Urban Downtown Scenario	3.2%	4.1%	96.8%	10.3%
Closed Tunnel Scenario	2.9%	3.8%	97.0%	8.7%
Heavy Rain Meteorological Scenario	3.1%	4.3%	96.5%	12.1%

Experimental data reveal that the average simulation error of the proposed platform remains below 3.2% across all complex scenarios with a maximum instantaneous error no higher than 4.3%, and the data fitting degree exceeds 96.5%. Compared with conventional integrated platforms, the simulation precision is improved by over 62%, enabling high-precision restoration of real vehicular wireless transmission characteristics.

5.5 Comparative Experimental Analysis of Architectural Performance

Comparative testing results against conventional platforms indicate that the scenario switching speed of the proposed modular platform is compressed from 80–120 ms to within 10 ms, representing an 87.5% improvement. Single-batch multi-scenario testing duration is reduced from 72 h to 38.8 h with a 46.2% rise in testing efficiency. The hardware resource reuse rate increases from 38.5% to 100%, and the continuous system operation failure rate drops from 8.3% to 0.67%, a reduction of 92%. The modular decoupling design fundamentally addresses the engineering problems of fixed architecture, difficult iteration, low testing efficiency and excessive errors plaguing traditional platforms, with remarkably enhanced engineering practicability.

6. Discussion

6.1 In-Depth Mechanism Analysis of Results

The significant improvement in simulation precision and testing efficiency of the proposed platform stems from two core mechanisms: first, the hierarchically decoupled architecture enables independent refined optimization of parameters for each module, avoiding systematic superposition errors introduced by deep coupling of multiple parameters in traditional integrated platforms and reducing systematic errors by over 60%; second, the multi-parameter coupled channel model combined with closed-loop iterative feedback realizes millisecond-level dynamic adaptive correction of channel parameters under time-varying scenarios, substantially narrowing dynamic deviations between simulation and measurement. Meanwhile, the standardized plug-and-play interface design fundamentally resolves the engineering problems of poor hardware adaptability, repeated adaptation and resource waste, greatly lifting testing efficiency and hardware utilization.

6.2 Comparison with Existing Literature Achievements

Different from existing research on vehicular simulation platforms that merely focus on single channel model optimization or individual function upgrades, this paper reconstructs the top-level architecture to establish a complete reconfigurable modular testing system. Average simulation errors of mainstream vehicular simulation platforms in existing literature generally exceed 8%, with most platforms supporting only single static scenarios and a hardware reuse rate below 45%. The proposed architecture realizes high-precision dynamic simulation of six typical scenarios with an average error as low as 3.2% and a 100% hardware reuse rate, delivering comprehensively superior performance indicators and stronger architectural universality and engineering implementability compared with state-of-the-art literature results.

6.3 Limitation Analysis of the Platform

Several optimization spaces remain for the proposed platform: first, there exists a 1%–2% precision improvement margin for ultra-high-speed extreme working conditions above 120 km/h and large-scale networking collaborative scenarios involving more than 50 vehicles (Liu Y & Wang L., 2025); second, the current interference model is dominated by controllable artificial quantitative interferences, failing to fully reproduce irregular random sudden electromagnetic interferences in field environments. Subsequent research will further optimize the simulation capability of complex extreme scenarios via artificial intelligence adaptive modeling.

7. Conclusions and Future Outlook

7.1 Main Conclusions

Targeting the problems of coupled architecture, fixed scenarios, insufficient precision and low reuse rate of traditional vehicular wireless test platforms, this paper completes modular architecture design, refined modeling and multiple groups of quantitative experimental verification. The core conclusions are summarized as follows:

1) The constructed four-layer hierarchically decoupled modular architecture achieves a module coupling degree as low as 0.28, realizing low coupling, high expandability and reconfigurability of the vehicular simulation test system with comprehensively improved performance compared with conventional architectures.
2) The established multi-parameter coupled vehicular channel model can accurately adapt to six typical driving scenarios, with the overall average simulation error lower than 3.2% and the maximum error limited to 4.3%, satisfying the high-precision industrial testing standard of ≤5% for vehicular communication.
3) The standardized plug-and-play interface design realizes compatible adaptation of multi-equipment and multi-standard devices, lifting the hardware reuse rate by 61.5% and testing efficiency by 46.2%, substantially cutting time and economic costs of vehicular communication testing.
4) The closed-loop automatic regulation mechanism supports dynamic iterative optimization of testing parameters with significantly enhanced automated and intelligent testing capacity, and the continuous operation failure rate is reduced to 0.67%, demonstrating outstanding engineering stability and application value.

7.2 Future Outlook

Subsequent research will deepen optimization from three aspects: first, introduce digital twin technology to construct a virtual-real integrated vehicular scenario simulation system for further improving simulation authenticity and precision under ultra-high-speed and large-scale networking extreme scenarios; second, integrate deep learning artificial intelligence algorithms to realize adaptive intelligent modeling of channel parameters and interference features for accurate fitting of random sudden electromagnetic interferences in field environments; third, expand the cloud-based distributed testing architecture to realize remote automated parallel testing of multi-terminal, multi-scenario and mass vehicular equipment, adapting to the testing demands of full-domain coordination and large-scale networking for future 6G Internet of Vehicles.

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