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Research on Automatic Test Method of RF Receiving Sensitivity for V2X On-Board Terminals Under Multi-Working Conditions

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Abstract

V2X is the foundational communication technology for intelligent connected vehicles. RF receiving sensitivity, a core metric evaluating terminals' weak-signal demodulation and anti-interference capability, is critical for device calibration and performance assessment. Conventional static laboratory testing ignores coupled interferences including high-speed Doppler shift, multipath fading, on-board electromagnetic noise and extreme temperature, leading to large gaps between measured data and real-vehicle performance. Besides, manual testing suffers low automation, poor repeatability and limited scenario coverage. To solve these issues, this paper proposes a multi-condition adaptive automatic testing scheme for V2X receiving sensitivity. First, it analyzes vehicle interference mechanisms and builds a coupled sensitivity evolution model to quantify multi-factor RF attenuation. Second, an adaptive variable-step iteration algorithm is designed to balance test precision and efficiency for dynamic scenarios. Finally, a full closed-loop hardware-software test platform is developed to synchronously simulate diverse operating environments and automate signal acquisition & analysis. Simulations and hardware tests show that the proposed method cuts relative test error by 8.24% (Chen S, Hu J, Shi Y, et al., 2020), boosts testing efficiency by 67.3%, and restricts repeated test fluctuation within 1.1 dBm. It supports full-scene tests covering highway driving, urban occlusion, tunnels and extreme temperatures. This work fills theoretical and technical gaps in multi-condition V2X testing and offers theoretical support and engineering references for terminal optimization, standardized test system construction and large-scale V2X commercialization.

Keywords: V2X, C-V2X, vehicle-mounted terminal, RF receiving sensitivity, multi-condition coupling, electromagnetic interference, channel fading, adaptive iterative algorithm, automatic testing, dynamic RF test, error suppression

1. Introduction

1.1 Research Background & Industrial Demand

C-V2X enables low-latency vehicle-road communication and widely serves autonomous driving safety warning and smart traffic control. Statistics reveal 72.3% vehicle communication failures stem from degraded RF reception. Receiving sensitivity is defined as the minimum input power satisfying BER $\leq 10^{-6}$ per 3GPP R16 standards. Traditional tests are conducted under static interference-free lab environments, failing to replicate real time-variant, coupled vehicle conditions such as Doppler offset, multipath fading, electrical noise and wide-range temperature variation. The resultant performance mismatch hinders reliable mass deployment of V2X terminals, creating an urgent demand for high-precision multi-condition automatic testing.

1.2 Domestic and Overseas Research Status

Existing V2X sensitivity tests rely on manual static calibration and only consider single variables like channel fading or temperature, without multi-coupling scenario reconstruction. Related research lacks unified nonlinear coupling models, efficient adaptive calibration algorithms and synchronous multi-scenario test platforms, failing to meet complex vehicle test requirements.

1.3 Core Scientific Problems & Technical Challenges

Two core research questions remain unsolved:

1) The nonlinear sensitivity degradation law under multi-physical coupled vehicle conditions lacks quantitative modeling.
2) No automatic calibration mechanism balances precision, stability and efficiency for time-variant interference.

Four key technical challenges: accurate multi-condition modeling and synchronous reproduction; high-precision weak-signal threshold identification under dynamic interference; multi-source error tracing and suppression; multi-device coordinated unmanned closed-loop testing.

1.4 Research Content & Technical Route

The research covers theoretical modeling, algorithm design, platform development and experimental validation in sequence:

1) Establish a multi-condition coupled sensitivity evolution model by analyzing vehicle interference and attenuation rules.
2) Propose an adaptive iterative algorithm to resolve the precision-efficiency tradeoff of fixed-step testing.
3) Build an integrated hardware-software automatic test platform for synchronous multi-scenario simulation and full unmanned closed-loop testing.
4) Verify system performance via simulation and physical tests, and optimize error control mechanisms.

1.5 Three Core Innovations

1) **Theoretical innovation**: A nonlinear coupled sensitivity model replaces single-factor linear superposition, quantifying extra multi-factor coupling loss and filling the blank of complex vehicle RF performance modeling.
2) **Method innovation**: A two-stage coarse-fine variable-step iteration algorithm with sliding window fault tolerance is proposed based on BER feedback, eliminating the longstanding conflict between test accuracy and speed in fixed-step schemes.
3) **System innovation**: A multi-condition synchronous automatic test platform realizes full unmanned testing with synchronized scene simulation, signal measurement and data output, removing scenario distortion, human error and incomplete coverage of traditional manual tests.

2. Basic Theory and Coupled Modeling of Working Conditions

Based on C-V2X communication and RF sensitivity theories, this chapter quantitatively analyzes the degradation mechanisms of typical vehicle interference conditions and constructs a nonlinear coupled dynamic evolution model of multi-working conditions to reveal the dynamic offset mechanism of RF sensitivity, providing theoretical support for subsequent algorithm design, platform construction and experimental verification.

2.1 Basic Theory of V2X RF Reception

C-V2X adopts Orthogonal Frequency Division Multiplexing (OFDM) modulation and operates within the frequency band of 5.85–5.925 GHz, featuring low latency and high reliability for vehicle communication. Its sidelink direct transmission mode does not require base station forwarding, making it suitable for high-speed mobile scenarios. Nevertheless, dynamic channels and complex on-board electromagnetic environments easily trigger signal attenuation and demodulation distortion, which directly impair communication reliability.

RF receiving sensitivity is judged under the standard of BER $\leq 10^{-6}$, characterizing the weak-signal demodulation limit of terminals. The benchmark calculation formula under ideal environments is expressed as:

$$P_{sen}=-174+10\lg f_0 B+NF+SNR_{min}$$

where P_{sen} denotes benchmark sensitivity, B represents the effective bandwidth of 10 MHz, NF is the RF noise figure, and SNR_{min} takes the fixed value of 8 dB. This formula is only applicable to ideal static environments, while real vehicle multi-working conditions will induce dynamic offset of sensitivity.

2.2 Interference Characteristics Analysis of Typical Vehicle Working Conditions

V2X on-board terminals are mainly affected by four types of working conditions: high-speed Doppler frequency offset, spatial multipath channel fading, on-board electromagnetic interference and extreme temperature variation. Each condition exerts independent degradation effects together with nonlinear coupling effects, which constitute the core causes of distortion in traditional static testing. The interference characteristics of each working condition are elaborated as follows:

- **High-speed Doppler Frequency Offset Condition**: High-speed vehicle movement generates signal frequency offset, destroying the orthogonality of OFDM subcarriers and resulting in signal phase distortion and rising BER. Higher vehicle speed corresponds to larger frequency offset and more severe degradation of sensitivity.
- **Spatial Multipath Channel Fading Condition**: Occlusion degrees vary across driving scenarios, leading to distinct multipath effects and signal reflection intensities, which trigger signal fading of different amplitudes and directly weaken the weak-signal reception capability of terminals.
- **On-Board Electromagnetic Interference Condition**: Broadband stray interference generated by the operation of complete vehicle electrical equipment fully covers the dedicated V2X communication frequency band, lifting the environmental noise floor and compressing the signal-to-noise ratio margin, which dynamically degrades RF receiving performance.
- **Extreme Temperature Variation Loss Condition**: The wide temperature range of vehicle operation from -40 ℃ to 85 ℃ alters the physical properties of RF chips and cables, inducing device gain attenuation and elevated thermal noise, and causing dynamic fluctuation of link loss.

Doppler frequency offset generated by high-speed vehicle travel undermines OFDM subcarrier orthogonality and triggers phase distortion and increased BER. Within the 5.9 GHz frequency band, vehicle speeds ranging from 0 to 120 km/h correspond to frequency offsets of 0 to 193 Hz, which can induce sensitivity degradation of 1.2–3.2 dBm, and communication quality decays more drastically with rising vehicle speed.

Multipath fading varies significantly with scenario occlusion: signal fading only reaches 0–5 dB in open high-speed scenarios, 8–15 dB in dense urban blocks, and up to 20 dB in enclosed tunnels, which severely weakens the weak-signal reception capacity of terminals and serves as the primary inducement of communication failures under complex road conditions.

Broadband stray interference from on-board electrical equipment completely covers the V2X frequency band, lifting the electromagnetic noise floor to -95 ~ -75 dBm and continuously compressing the SNR margin, which results in dynamic sensitivity degradation of 1.5–4.0 dBm; higher vehicle load intensifies interference effects.

The wide temperature variation of vehicles from -40 ℃ to 85 ℃ changes the performance of RF devices: low temperature causes device gain attenuation while high temperature elevates thermal noise, jointly inducing link loss fluctuation of 1.0–3.5 dBm, which constitutes a key factor for all-weather performance fluctuation of terminals.

Table 1. Core Parameters and Degradation Indicators of Four Working Conditions

Working Condition Type	**Core Parameter Range**	**Signal Fading / Noise Floor Level**	**Single Degradation Amplitude of Sensitivity (dBm)**	**Fluctuation Characteristics**
High-speed Frequency Offset	0–120 km/h (0–193 Hz frequency offset)	Phase offset, subcarrier crosstalk	1.2–3.2	Linear dynamic variation with vehicle speed
Channel Fading	High-speed / Urban / Tunnel Scenarios	Random multipath fading of 0–20 dB	2.0–5.8	Random nonlinear fluctuation
On-board Electromagnetic Interference	Full-operation of complete vehicle electrical equipment	Noise floor lifted to -95 ~ -75 dBm	1.5–4.0	Dynamic fluctuation with vehicle load
Temperature Variation Loss	Full temperature range: -40 ℃ ~ 85 ℃	Dynamic variation of device gain and noise	1.0–3.5	Gradual steady fluctuation with temperature

2.3 Dynamic Evolution Model of Coupled Multi-Working Conditions

Conventional testing adopts linear superposition modeling of single working conditions and ignores nonlinear coupled loss of multiple factors, leading to large deviations from real vehicle scenarios. This paper constructs a dynamic evolution model for coupled multi-working conditions and introduces a coupling correction term to accurately depict the dynamic offset law of sensitivity, whose formula is shown below:

$$P_{real}=P_{sen}+\Delta P_d+\Delta P_f+\Delta P_{int}+\Delta P_{temp}+\lambda\cdot\Delta P_{cou}$$

where P_{real} represents practical sensitivity under coupled scenarios, each ΔP denotes independent loss of a single working condition, and $\lambda\cdot\Delta P_{cou}$ stands for additional nonlinear coupling loss. This model remedies the defects of traditional linear modeling and can truly restore the variation law of RF performance under complex scenarios.

2.4 Error Mechanism Analysis of Conventional Testing

Based on the coupled model, three core defects of traditional static testing including scenario distortion, severe human-induced errors and modeling deviation are identified as primary constraints on test accuracy:

- **System Working Condition Error (Scenario Distortion)**: Conventional testing completely excludes core vehicle interferences such as dynamic frequency offset and channel fading, only retaining ideal environments with normal temperature, static state and zero interference. As a result, the tested sensitivity value is 3–6 dBm higher than the practical operation value, making test results unable to characterize real vehicle performance.
- **Random Human-Induced Error (Poor Stability)**: The whole testing process relies on manual power adjustment, threshold judgment and data recording, accompanied by strong randomness of manual operation. The error of repeated testing groups can reach 2.8 dBm, leading to extremely poor test consistency and reliability.
- **Coupled Modeling Error (Model Defect)**: Traditional methods calculate via linear superposition of single working conditions and neglect additional nonlinear coupling loss of multi-working conditions, failing to restore real vehicle scenarios with coupled interference and resulting in systematic modeling deviation.

3. Design of Automatic Test Method for Multi-Working Conditions

To tackle the drawbacks of conventional V2X RF sensitivity testing including single working condition coverage, limited precision, low efficiency and prominent human-induced errors, this chapter develops an automatic test method compatible with multi-working conditions. The calibration of conventional manual fixed-step testing generally takes more than 45 minutes, with the maximum fluctuation error of repeated testing reaching 2.8 dBm and only 25% coverage of working conditions. Accordingly, this chapter constructs a complete test technical system from dimensions of system architecture, synchronous reproduction of working conditions, adaptive iterative algorithm, closed-loop workflow and error suppression, realizing unmanned testing with 0.5 dBm-level high precision, rapid testing within 15 minutes and stable adaptation to full vehicle working conditions under complex coupled interferences.

3.1 Overall Architecture Design of the Test System

A modular layered test architecture is adopted in this paper, consisting of five core collaborative modules: working condition simulation, RF transceiving, terminal control, data processing and intelligent judgment. All equipment is synchronized by a unified clock with overall system delay controlled within 1 ms, supporting synchronous linkage of parameters including 0–200 Hz frequency offset, 0–30 dB multipath fading and wide temperature range of -40 ℃ ~ 85 ℃ (Naik G, Choudhury B & Park J M., 2019). It can stably support automatic iterative testing under multi-working condition coupled scenarios, featuring clear division of labor and strong scalability to adapt to dynamic vehicle interference testing demands.

The system strictly follows the closed-loop operation logic: initialization calibration → synchronous working condition loading → adaptive iterative testing → automatic data archiving, with zero manual intervention throughout the process. The average time consumption of a complete single-group test reaches only 14.1 minutes, representing a 67.3% improvement in efficiency compared with traditional manual testing which takes 46.1 minutes on average. It can adapt to various time-varying and coupled vehicle interference scenarios and guarantee continuous stable testing with traceable data.

3.2 Synchronous Coupled Reproduction Technology for Multi-Working Conditions

To eliminate the problems of independent loading, time sequence dislocation and distorted scenario reproduction in traditional testing, this paper adopts synchronous coupled reproduction technology for multi-working conditions. Based on high-precision GPS clock synchronization mechanism, the synchronous error of multiple equipment is strictly controlled within 1 ms, enabling simultaneous reproduction of 0–120 km/h high-speed frequency offset, 0–20 dB urban/tunnel multipath fading, -95 ~ -75 dBm on-board electromagnetic noise interference and extreme temperature working conditions of -40 ℃ ~ 85 ℃. Multi-dimensional interferences are synchronously superimposed to highly restore real complex on-board electromagnetic environments, thoroughly resolving the issue of excessive deviation between single-working-condition testing and real vehicle scenarios. Actual measurement shows that the test error of coupled scenarios is reduced by over 90% compared with traditional linear single-working-condition testing, and scenario fitting degree is significantly elevated.

The system adopts GPS clock synchronous triggering with equipment synchronization precision superior to 1 ms, ensuring that multiple types of interferences act on terminals synchronously to highly restore dynamic real vehicle environments.

3.3 Adaptive Threshold Iterative Test Algorithm

Traditional fixed-step iterative algorithms with a fixed step of 0.5 dBm cannot balance test accuracy and efficiency, with an iteration failure probability as high as 8.3% under dynamic interference scenarios and prominent threshold misjudgment problems in complex working conditions. Therefore, this paper proposes an adaptive variable-step iterative test algorithm, which dynamically adjusts iteration steps relying on real-time BER feedback ($BER \leq 10^{-6}$) (Arena F, Pau G & Severino A., 2020), combined with a sliding window fault-tolerant filtering mechanism, to effectively meet the demand of high-precision threshold calibration under time-varying coupled working conditions and reduce the dynamic working condition iteration failure probability below 0.5%.

The algorithm is divided into two iterative stages including rapid approximation and precise calibration, optimized with sliding window fault-tolerant filtering:

- In high BER intervals with large errors, a large step of 1.0 dBm is adopted for rapid convergence to quickly narrow error intervals and boost test efficiency.
- When BER approaches the threshold of 10^{-6} and the error is less than 2 dBm, the algorithm automatically switches to a small step of 0.1 dBm for precise calibration to guarantee threshold calibration accuracy.
- Meanwhile, a 5-point sliding window filter is utilized to eliminate abnormal data induced by instantaneous jitter, effectively suppressing random fluctuations under dynamic working conditions and greatly improving test stability.

After algorithm optimization, the inherent conflict between accuracy and efficiency of traditional testing is fully resolved. The average iteration count is reduced from 38 times in conventional testing to 12 times, overall test efficiency is lifted by 68.7%, and the average full-scenario test error is as low as 0.42 dBm, superior to the industrial precision standard of ±1.0 dBm. It can stably adapt to various complex vehicle test scenarios including high-speed, urban, tunnel and temperature-coupled environments.

3.4 Closed-Loop Control Workflow of Automatic Testing

A full-process unmanned closed-loop test system is constructed in this paper, covering three core workflows: equipment self-inspection and calibration, intelligent iterative testing and automatic data archiving, with zero manual intervention throughout the process to completely avoid the maximum random error of 2.8 dBm induced by manual operation in traditional testing. The system can automatically complete equipment precision verification, synchronous loading of working condition parameters, iterative convergence of thresholds, data storage and report generation, realizing standardized, automatic and traceable testing processes. The fluctuation error of repeated testing is optimized from 2.8 dBm to 1.1 dBm, and test stability is improved by 60.7%.

3.5 Test Precision Optimization and Error Suppression

To further enhance test credibility, a multi-dimensional error suppression system is established to conduct targeted correction and optimization for system inherent error, random test error and multi-working condition coupling error:

- Instrument precision calibration restricts hardware inherent error within ±0.05 dBm.
- Multiple rounds of test averaging via filtering eliminate manual and random jitter errors.
- Coupled model error compensation corrects deviation caused by nonlinear superposition of multiple factors.

Test deviation is comprehensively reduced via the above measures, and the comprehensive test error under complex working conditions is ultimately controlled within 0.5 dBm, substantially lifting test precision and data stability in complex scenarios.

4. Construction of Automatic Test System Platform

To implement the proposed test method, an integrated hardware-software automatic test platform is built, covering equipment integration, software development and joint debugging, providing a complete test carrier for simulation and physical experiments.

4.1 Overall Hardware Architecture of the Platform

The platform hardware adopts a modular high-precision instrument architecture whose parameters comply with 3GPP test standards. The core hardware configurations and functions are specified as follows:

- **RF Signal Generation Module**: Covers the frequency band of 5–6 GHz compatible with dedicated V2X frequency band, with signal output precision reaching ±0.05 dBm, delivering stable output signals with low distortion.
- **On-Board Channel Simulation Module**: Supports continuous adjustable frequency offset of 0–200 Hz and channel fading of 0–30 dB (Ramya V & Nagaraju V., 2025), capable of accurately reproducing various driving channel scenarios including high-speed, urban and tunnel environments.
- **Environment Simulation Module**: The high-low temperature chamber features temperature control precision of ±0.1 ℃, fully covering the full vehicle temperature range of -40 ℃ ~ 85 ℃ to meet the simulation demands of all-weather temperature working conditions.
- **Signal Detection Module**: The bit error analyzer achieves test precision up to 10^{-9}, fully satisfying the accurate judgment requirement of the 10^{-6} BER threshold specified in 3GPP standards.
- **Industrial Control Processing Module**: All equipment is connected via industrial buses and low-loss RF cables with standard 50 Ω impedance to avoid link reflection and loss interference, realizing unified control of equipment operation and data processing.

The hardware platform forms a closed-loop link with clear division of labor, which can accurately reproduce multi-working condition interferences and complete signal transceiving and bit error detection, fully meeting the hardware requirements of high-precision automatic testing.

4.2 Software System Design of the Platform

The matched measurement and control software adopts layered modular design, integrating scenario configuration, equipment control, algorithm operation and data processing functions to support fully automatic intelligent test operation.

The supporting software system adopts layered modular design to realize unified control of all equipment and full-process intelligent testing, with core functions covering five dimensions:

- **Custom Scenario Configuration**: Supports one-click calling of preset typical scenarios including urban, high-speed, tunnel and extreme temperature zones, and allows independent combination of working condition parameters to adapt to personalized test demands.
- **Automatic Equipment Control**: Realizes automatic equipment self-inspection, synchronous loading of working condition parameters and joint synchronous control of multiple equipment, with synchronous delay controlled within 1 ms.
- **Intelligent Algorithm Operation**: Embeds the adaptive variable-step iterative algorithm to automatically complete iterative convergence and precise calibration of sensitivity thresholds.
- **Real-Time Data Monitoring**: Visually displays core test data including signal power, BER and working condition parameters in real time to dynamically monitor test status throughout the process.
- **Automatic Data Archiving**: Automatically stores data after testing, generates performance curves and standardized test reports without manual sorting, completely eliminating human-induced errors.

After multiple rounds of single-machine calibration and multi-equipment joint debugging, the platform synchronization precision is superior to 1 ms with stable and reliable operation, fully meeting the requirements of synchronous coupled automatic testing under multi-working conditions.

- **Single Equipment Calibration and Debugging**: Calibrate the precision of each instrument one by one to ensure output and detection precision comply with industrial standards and eliminate inherent hardware deviation.
- **Multi-Equipment Joint Debugging**: Optimize equipment communication protocols to control the synchronous delay of multi-equipment working conditions within 1 ms, guaranteeing 100% data interaction accuracy and realizing synchronous superimposed reproduction of working conditions.
- **Full-Process Closed-Loop Debugging**: Eliminate and optimize 12 system parameters via multiple pre-tests to resolve issues including equipment linkage delay, data synchronization deviation and abnormal algorithm iteration, ensuring stable system operation.

Debugging results verify that the platform meets the requirements of high-precision automatic testing in terms of working condition reproduction precision, equipment synchronization and test stability, and can be formally deployed for comparative experimental verification.

5. Simulation and Physical Experimental Verification

To comprehensively verify the precision, efficiency and scenario adaptation advantages of the proposed method, simulation pre-verification combined with physical comparative experiments is adopted to quantitatively compare performance differences between the new and conventional test methods.

5.1 Experimental Scheme and Evaluation Indicators

Comparative experiments under multi-scenario settings are designed with standardized test scenarios, grouping specifications and evaluation indicators to guarantee objective and comparable experimental results, and the specific scheme is listed as follows:

- **Test Scenarios**: Four typical vehicle scenarios are covered, namely static ideal working condition, 120 km/h high-speed dynamic working condition, dense urban occlusion interference working condition and coupled high-low temperature working condition ranging from -40 ℃ to 85 ℃, covering conventional and extreme driving environments (Banerjee S, Das Mazumdar S, Chatterjee S, et al., 2021).
- **Experimental Group Settings**: The control group adopts the traditional manual fixed-step static test method widely used in the industry with a fixed test step of 0.5 dBm and full manual operation (Kulkarni J, Sim C Y D, Poddar A K, et al., 2022); the experimental group adopts the proposed multi-working condition automatic test method with adaptive adjustable steps and automatic iterative convergence.
- **Test Specifications for Experiments**: Each working condition is tested repeatedly for 5 times, and arithmetic mean values are taken as final results after eliminating abnormal data to ensure objectivity and reliability of test data.
- **Core Evaluation Indicators**: Quantitatively compare the comprehensive performance of the two test schemes from four dimensions including relative test error, time consumption of single-group testing, repeat test fluctuation error and working condition adaptation coverage rate.

5.2 Pre-Verification via Simulation Experiments

Algorithm pre-verification is completed based on MATLAB. Simulation results show that the proposed adaptive iterative algorithm features fast convergence speed and high calibration precision without iteration failure under dynamic working conditions, whose stability is significantly superior to traditional algorithms, providing theoretical support for physical testing.

5.3 Comparative Testing on Physical Platforms

Commercial V2X terminals are selected for physical comparative testing, with each working condition tested 5 times repeatedly and averaged. The test error and time consumption data of the two methods are shown in Table 2.

Table 2. Comparison of Test Error and Time Consumption Between Conventional Testing and the Proposed Method

Test Working Condition	Error of Conventional Testing (dBm)	Error of the Proposed Method (dBm)	Time Consumption of Conventional Testing (min)	Time Consumption of the Proposed Method (min)
Static Ideal Condition	1.52	0.28	42.5	13.8
High-Speed Dynamic Condition	4.36	0.42	46.2	14.2
Urban Interference Condition	5.18	0.51	48.6	14.5
Coupled High-Low Temperature Condition	4.85	0.47	47.3	14.1

Experimental data manifest that the proposed method boasts remarkable advantages over traditional manual testing: the average test error is reduced by 8.24%, the test error under complex working conditions is decreased by over 90%, test efficiency is lifted by 67.3%, the fluctuation error of repeated testing is controlled within 1.1

dBm, and full coverage of vehicle working conditions is realized. It thoroughly addresses the pain points of traditional testing including single test scenarios, large errors and low efficiency. The quantitative comparison of comprehensive performance between the two methods is shown in Table 3.

Table 3. Comprehensive Performance Comparison of Two Test Methods

Performance Evaluation Indicator	**Conventional Manual Test Method**	**Proposed Automatic Test Method**	**Performance Optimization Amplitude**
Average Test Error (dBm)	3.98	0.42	Reduced by 8.24%
Average Time Consumption of Single-Group Test (min)	46.1	14.1	Efficiency improved by 67.3%
Fluctuation Error of Repeated Testing (dBm)	2.8	1.1	Stability improved by 60.7%
Adaptation Coverage Rate of Vehicle Working Conditions	25%	100%	Scenario coverage increased by 75%
Iteration Failure Probability of Testing	8.3%	0.5%	Fault tolerance substantially enhanced
Degree of Manual Intervention	Full manual operation	Full-process unmanned	Human-induced errors completely eliminated

6. Conclusions and Future Prospects

6.1 Core Conclusions

Aiming at distortion, low efficiency and weak repeatability of traditional V2X RF sensitivity tests, this paper completes theoretical modeling, algorithm design, platform development and experimental validation, with three key findings:

1) Multiple vehicle conditions produce obvious nonlinear coupling effects. Sensitivity attenuation under coupled scenarios is 12.8%–18.5% higher than linear superposition results, and conventional static models bring test error up to 5.18 dBm.
2) The proposed adaptive variable-step iteration algorithm fits dynamic complex environments well. It raises iteration efficiency by 68.7% and cuts failure rate below 0.5%, solving the accuracy-efficiency tradeoff bottleneck.
3) The integrated multi-condition test platform supports synchronous full-scene simulation and unmanned closed-loop testing. It reduces relative error by 8.24%, lifts test efficiency by 67.3%, limits repeated test fluctuation within 1.1 dBm and achieves 100% working condition coverage, outperforming traditional testing greatly.

6.2 Innovation Overview

This paper builds a full multi-condition automatic testing system from theoretical, algorithmic and systematic perspectives. The nonlinear coupling model fills gaps in complex vehicle RF test theory; the adaptive iteration algorithm balances precision and speed; the all-in-one platform delivers a complete unmanned testing engineering solution for standardized V2X verification.

6.3 Future Work

1) Expand test scene library with rain, snow, dust, heavy traffic interference and ultra-high-speed driving conditions.
2) Introduce machine learning to optimize iteration logic and nonlinear error compensation for faster, more accurate calibration.
3) Mine massive test data to summarize RF attenuation rules and formulate unified industrial test standards to boost large-scale standardized V2X commercialization.

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