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Article

Modeling and predicting the transmission efficiency of communication devices under joint noise and vibration disturbances

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Abstract: In complex environments such as industrial sites and rail transit, communication equipment often faces multi-source interference from mechanical vibration and structural noise, which seriously affects its signal quality and transmission stability. Although previous studies have explored the influence mechanism of a single interference source, there is still a lack of in-depth understanding and quantitative modeling of the coupled interference effect of vibration and noise. To this end, this paper builds an experimental platform based on the ESP32 Wi-Fi communication module, which includes controllable electromagnetic vibration and sound pressure loading, and collects communication performance indicators (RSSI, BER, throughput and delay) and synchronous physical disturbance data under different interference conditions. Through multivariate statistics and variance analysis methods, the interaction law between vibration frequency, amplitude and noise sound pressure level is revealed for the first time. It is found that the combination of the two under medium and high intensity conditions will cause significant nonlinear amplification effects, which will have a synergistic degradation effect on communication performance. The long short-term memory neural network (LSTM) is further introduced to construct a time series prediction model under multi-disturbance environment. The results show that the model has excellent fitting accuracy ($R^2 > 0.97$) in RSSI and throughput prediction tasks, which is better than the comparison models such as SVM and polynomial regression, and has good feedforward control potential. The study also proposed communication anti-interference optimization suggestions and equipment structure improvement strategies suitable for industrial and rail scenarios, providing a theoretical basis and experimental support for the intelligent adaptive design of wireless communication systems in high-interference environments.

Keywords: communication equipment; noise interference; mechanical vibration; performance modeling; LSTM prediction; anti-interference communication

1. Introduction

With the widespread application of wireless communication technology in industrial manufacturing, rail transit, underground pipelines and high-intensity working environments, the stability and reliability of communication systems are facing more and more challenges from the physical environment [1]. In such typical complex scenarios, communication equipment not only has to deal with high-speed movement and multipath interference, but also has to be exposed to strong mechanical vibration and environmental noise for a long time. Existing studies have focused on technical issues such as wireless channel modeling, electromagnetic interference and transmission protocol optimization. However, the change law of communication performance in high vibration and high noise environments has not been systematically and deeply quantitatively studied [2,3]. However, in fact, mechanical vibration can cause slight changes in the structure of the communication module, affecting antenna performance and channel status [4]. At the same time, structural noise (such as track collision and mechanical shock) may also introduce random interference through electromagnetic coupling or hardware links, thereby causing signal attenuation, unstable transmission power and increased bit error rate [5].

Although vibration and noise often coexist in real working conditions, most current research still focuses on analyzing their individual impact on communication performance. Research on the possible coupling effects, cooperative interference mechanisms, and their impact on channel quality change paths is still relatively scarce. This “interactive disturbance” is particularly critical in engineering practice, because actual communication systems are often in the structural resonance zone, the acoustic-vibration superposition zone, or the load nonlinear zone, and a single disturbance model is difficult to accurately evaluate the system stability. Therefore, in-depth exploration of the coupling mechanism of noise and vibration and the construction of a performance modeling method that can predict their joint impact are key breakthroughs in improving the reliability and intelligent control capabilities of communication systems in complex environments. Studying the joint impact of mechanical vibration and noise on the transmission efficiency of communication equipment not only helps to reveal the underlying physical mechanism of channel quality changes, but also has important engineering value for the reliable operation of communication equipment in complex working environments. This study will make up for the lack of understanding of the coupling mechanism between physical interference and communication performance in existing research, and provide theoretical support and experimental basis for the design, performance evaluation and adaptive optimization of communication systems for extreme environments in the future.

This study builds an experimental platform with ESP32 Wi-Fi communication module as the core, comprehensively considers the influence mechanism of mechanical vibration and environmental noise on wireless communication performance, and systematically carries out theoretical analysis, experimental testing and model construction around the theme of “communication performance modeling and prediction under physical disturbance”.

The research content mainly includes the following aspects: First, build an experimental platform including controllable vibration loading and noise interference devices, introduce electromagnetic vibration table to simulate mechanical disturbances of different frequencies and amplitudes, and simulate common structural noise sources in industrial environments (such as electric drill sound, impact sound, etc.) through audio playback system. Secondly, set ESP32 module as communication terminal, build point-to-point or point-to-multipoint communication link, collect key performance indicators such as signal strength (RSSI), bit error rate (BER), throughput, connection delay in real time, and record vibration and noise data simultaneously. Then, multivariate statistics and feature analysis methods are used to explore the laws and interactive effects of noise and vibration on communication performance. Finally, a joint modeling and prediction framework is constructed, and a performance prediction model is established based on a deep neural network (such as LSTM), and its accuracy and adaptability are verified through experiments.

This paper revolves around the law of communication performance changes under physical disturbance environments, and the overall structure is arranged as follows: Section 1 is an introduction, which mainly introduces the research background and significance of the topic, clarifies the research content, objectives and methods, and outlines the overall framework of the paper. Section 2 is a review of related research, which mainly sorts out the research results at home and abroad in vibration and noise interference, wireless communication performance modeling and environmental adaptive technology, and summarizes the research gaps and development trends. Section 3 is the design of the experimental system, which details the communication equipment and sensor modules used, the experimental platform construction method, and the data acquisition and processing process. Section 4 is an analysis of experimental results, focusing on the communication performance under different vibration frequencies, noise types and intensity combinations, and exploring its influence rules. Section 5 is a discussion, which systematically discusses the combined influence mechanism of noise and vibration on communication performance and the application value of the prediction model, and proposes optimization suggestions for communication system anti-interference and equipment anti-vibration in combination with industrial sites and rail transit scenarios. Section 6 is a conclusion and prospect, which summarizes the research results, points out the research limitations, and looks forward to future expandable research directions and technical routes.

This study aims to construct a systematic communication performance evaluation method under the influence of multiple factors, quantify the impact of different noise and vibration intensity combinations on communication quality, and provide a theoretical basis and engineering strategy for the design and anti-interference optimization of communication systems in high interference environments.

2. Related work

In complex physical environments, the transmission stability and reliability of wireless communication systems are affected by a variety of external factors. Especially in scenarios such as industrial workshops, rail transit, and high-speed machinery operation, mechanical vibration and environmental noise are common interference sources that may cause serious interference to key performance indicators such as the channel state, data transmission quality, and energy efficiency control of communication equipment [1]. This section will review the current status of noise interference research, the progress of vibration interference research, and communication performance modeling and prediction methods, providing theoretical support and technical reference for subsequent modeling and experimental research.

2.1. Physics of vibration and noise under complex working conditions

In complex industrial sites, communication systems are often deployed in spaces close to heavy machinery and equipment or rail operation areas, and are subject to the influence of multi-source physical disturbances for a long time, among which vibration and noise are the most common and most destructive forms of interference. From the perspective of physical mechanism, these disturbances mainly come from mechanical systems such as large motors, centrifugal pumps, air compressors, transformers, and rail vehicle wheel-rail impacts. During operation, they will produce periodic or non-periodic mechanical excitations, resulting in dynamic disturbances in the environment where the communication module is located with predictable frequency but uncontrollable amplitude [6].

The propagation of vibration is mainly structural conduction, and it often spreads to the surrounding area in the form of longitudinal waves or shear waves through solid media such as equipment bases, steel frames, housings, and supporting pipes, forming local resonance or even system resonance. When the communication module is directly installed on the structural support, its internal components are very susceptible to mechanical stress concentration, affecting the stability of the signal circuit [7].

In contrast, noise is mainly propagated by acoustic radiation, which radiates to the surroundings with the help of air medium, forming far-field sound pressure or near-field resonance zone. If it is in a closed space or a space with dense reflection interfaces, it may also form standing waves [8]. Structural noise is mostly broadband non-stationary sound, such as welding, electric drilling, metal collision and high-pressure airflow. These noise bands have a significant impact on wireless communication receiving modules, mainly manifested as electromagnetic coupling interference, weak capacitive induction or audio disturbance superposition on antennas and RF front-end circuits, especially in metal shells or reverberant field environments, local sound pressure superposition and amplitude jumps are prone to occur, affecting the modulation and demodulation process [9]. Therefore, the vibration frequency, amplitude and noise sound pressure level selected in the experimental platform of this paper refer to the energy spectrum characteristics of typical interference sources in the above engineering scenarios to ensure that the experimental settings are representative and comparable in terms of physical mechanisms and engineering environments. This physical basis provides theoretical support and parameter basis for subsequent communication performance degradation mechanism analysis and modeling prediction.

2.2. Research status of noise interference on communication performance

As one of the major sources of interference in communication systems, noise has long been a research focus in signal processing and anti-interference design [10]. In traditional communication theory, noise is often modeled as additive white Gaussian noise (AWGN), and its impact on channel capacity and bit error rate can be accurately described by Shannon's formula and bit error analysis [11]. However, the actual noise types in the industrial and transportation fields are often structural noise or broadband impulse noise. This type of noise has the characteristics of non-stationarity, strong periodicity, and large amplitude variation, which is not easy to be accurately described by traditional models [12].

In recent years, researchers have begun to pay attention to the actual impact of structural noise on wireless devices. Some studies have found that high-intensity noise can not only affect the circuit stability of the signal transmission module through electromagnetic coupling, but also cause resonance interference in the audio frequency band, thereby causing channel quality degradation and increased data packet loss rate

[13,14]. Overall, the current research on the mechanism of how acoustic noise in non-electrical signal paths affects communication performance is still in its infancy, lacking systematic modeling and large-scale experimental data support.

2.3. Research progress on vibration interference on communication systems

Compared to noise interference with vibration as a source of mechanical disturbance, more directly affects the structural integrity of communications equipment, connection stability and electrical parameters [15]. Studies have shown that long-term vibration can lead to problems such as solder joint fatigue, antenna offset, and connector loosening, thereby causing signal fluctuations and equipment performance degradation [16–18]. In scenarios such as high-speed trains, drones, and elevator control systems, communication systems are frequently in medium- and high-intensity vibration environments, and stability assurance faces challenges.

Some studies have explored the disturbance mechanism of vibration on antenna return loss from an electromagnetic perspective, and experimentally found that high-frequency and small-amplitude vibrations can cause antenna pattern offset and signal gain reduction [19]. Another part of the research focuses on the microscopic deformation of PCB boards during vibration, and analyzes the performance changes of circuit components through finite element analysis and thermal-mechanical coupling models, indirectly revealing the mechanism of vibration interference [20,21].

However, the current analysis of the specific mapping relationship between vibration amplitude-frequency characteristics and communication performance is still insufficient, especially in terms of the impact mechanism under the conditions of combined multiple disturbance sources (such as vibration + noise), and there is a lack of systematic experimental verification and modeling methods.

2.4. Research on communication performance modeling and prediction methods

In view of the impact of environmental interference on communication performance, a variety of modeling and prediction methods have been proposed, which can be mainly summarized into two categories: statistical modeling and data-driven modeling [22,23]. The former is usually based on traditional physical modeling and regression analysis, such as multivariate linear regression, generalized linear model (GLM), ridge regression, etc., emphasizing the causal and significant relationship between variables, and is suitable for describing stable linear response relationships [24]. However, in the face of nonlinear disturbance environments (such as noise-vibration coupling), traditional models often face problems of insufficient fitting or poor generalization ability.

In recent years, researchers have begun to introduce machine learning and deep learning methods to predict communication performance indicators [25,26]. This type of method can handle multi-input, multi-dimensional time series data and has strong feature extraction and nonlinear modeling capabilities. For example, Qu et al. used LSTM networks to dynamically predict RSSI and BER in LTE environments and achieved better results [27]. In order to solve the problems of insufficient damage identification accuracy of complex frame structures and insufficient utilization of multi-sensor data, a damage identification method based on CNN and multi-channel data fusion was proposed, which has higher identification accuracy. Its noise resistance and effectiveness were verified in numerical models and experimental tests [28].

Nevertheless, most current modeling methods are still based on ideal or single interference scenarios, lacking the ability to comprehensively model and predict the communication performance change mechanism under multi-physical disturbance conditions (especially noise and vibration coupling). At the same time, the number of experimental data samples is limited, and the model generalization and interpretability are insufficient.

2.5. Summary and research entry point

In summary, although there are preliminary results in the current research on the impact of noise and vibration on the performance of communication equipment, most of them focus on the impact assessment of a single interference source, and a unified modeling framework for changes in communication performance under multi-source physical disturbances has not yet been formed. Especially under the coupling of noise and vibration, the coupling interference mechanism, performance degradation path and prediction method of the communication module are still unclear, which limits the design optimization and reliable operation guarantee of the communication system in a high-interference environment.

Therefore, this paper will systematically carry out experimental data collection based on actual industrial-grade communication modules and vibration/noise loading platforms, and construct a communication performance prediction model considering the noise-vibration dual disturbance characteristics, aiming to fill the research gap in this field in joint modeling and non-ideal scenario adaptability evaluation, and provide data and model support for the design of anti-interference communication systems in complex environments.

3. Method

In order to deeply explore the comprehensive impact of noise and vibration interference on the transmission performance of communication equipment in industrial environments, this paper builds a controllable and repeatable experimental platform based on the ESP32 Wi-Fi communication module, combines a multi-physics disturbance loading device with a communication performance test system, and systematically carries out experimental data collection, feature analysis, and predictive modeling. This section will introduce in detail the construction of the experimental platform, communication system deployment, interference source design, data collection methods, and modeling and prediction processes.

3.1. Experimental platform construction

The experimental platform takes the ESP32 communication module as the core, combines mechanical vibration loading and structural noise interference system, and builds a highly controllable physical interference simulation environment to simulate high noise and vibration interference in industrial sites and rail transportation. The platform mainly consists of the following parts:

(1) Communication system: a point-to-point (P2P) or point-to-multipoint (P2MP) Wi-Fi link built with the ESP32 communication module to perform the task of timing data packet transmission;

(2) Vibration loading system: an electromagnetic excitation table is used to simulate mechanical disturbances of different frequencies (10 Hz–1000 Hz) and amplitudes (0.1 g–5 g);

(3) Noise interference system: a high-power speaker and an audio player are used to play common industrial structural noise (such as electric drill sound, impact sound, metal friction sound, etc.), with a sound pressure level of 60 dB–100 dB;

(4) Sensing and synchronization module: a noise meter and an acceleration sensor are arranged to record the ambient sound pressure level and mechanical acceleration data, and the timestamps are aligned uniformly through the main control system;

(5) Data processing system: a Python-based host computer program is built to collect communication performance indicators and interference parameters in real time and save them in a standardized data format.

The platform design supports multiple rounds of interference combination testing and parameter adjustment to meet the needs of systematic analysis between communication performance and interference variables.

3.2. Communication module deployment and performance indicator collection

The experiment selected the ESP32 module as the communication node. The module has stable Wi-Fi communication capabilities, low-power operation characteristics, and convenient RSSI, throughput and bit error rate collection interfaces.

In the specific experiment, the ESP32 communication system was configured to periodically send fixed-length data packets and receive and record communication results in real time. The key performance indicators collected include:

- RSSI: reflects channel quality;
- BER: reflects signal decoding accuracy;
- Throughput: the amount of data successfully transmitted per unit time;
- Connection delay (Latency): the time delay from the sending of a data packet to the confirmation of receiving.

The performance data is uploaded to the host computer synchronously through the UART interface, and is uniformly marked and recorded with the values collected by the vibration and noise sensors to form a multi-source collaborative observation data set.

3.3. Design of vibration and noise interference

In order to be as close as possible to the actual working conditions in industrial sites, rail transit and high-noise environments, this paper introduces two typical interference sources into the experimental platform: mechanical vibration disturbance and structural noise interference. These two types of interference often coexist in actual application scenarios and have a potential superposition effect on the transmission quality of wireless communication systems. Therefore, when designing experiments, their independent effects and interaction effects need to be fully investigated.

In terms of vibration disturbance, the experiment uses an electromagnetic vibration table as a loading device, which can accurately control the frequency and amplitude of the output signal [29]. Specifically, the sine wave signal controller sets different frequencies and different acceleration amplitudes to simulate the vibration environment of communication equipment under typical mechanical disturbance conditions. At the same time, the system also supports loading random vibration waveforms to simulate the non-periodic disturbances generated during the operation of complex industrial equipment, thereby more comprehensively revealing the sensitivity and robustness of communication performance to vibration characteristics.

In terms of noise interference, the platform is equipped with high-fidelity speakers and power amplifiers to play audio files covering a variety of industrial noise characteristics. These audio signals include those collected from real industrial environments (such as factory electric drill operation sounds, mechanical impact sounds, and arc sounds during welding), as well as typical structural noise constructed by synthetic means (such as low-frequency oscillation sounds, high-frequency sharp alarm sounds, etc.) [30]. The playback sound pressure level is adjustable, ranging from 60 dB to 100 dB, to simulate the interference effects of noise environments of different intensities on communication equipment. Real-time monitoring of the sound pressure level is completed by a professional sound level meter and recorded synchronously in the experimental data system.

In the design of the experimental scheme, considering that vibration and noise may exist separately or simultaneously in actual applications, the experiment sets up three types of test modes: the first is a single-factor noise disturbance experiment, in which noise signals of different sound pressure levels are loaded under the condition of no mechanical vibration; the second is a single-factor vibration disturbance experiment, in which vibration signals of different frequencies and amplitudes are loaded under a noise-free environment; the third is a dual-factor joint disturbance experiment, in which a specific combination of vibration and noise signals is loaded synchronously to simulate the most challenging composite interference scenario. In each set of experiments, key performance indicators such as RSSI, bit error rate, throughput and delay of the ESP32 communication module are collected, and combined with the synchronously collected sound pressure and vibration data to provide sufficient data support for subsequent interactive analysis and modeling prediction.

Through the above design, this experimental platform can systematically explore the impact mechanism of different types of interference on communication performance, and provide an experimental basis for the anti-interference design of communication systems under multi-physical field interference.

3.4. Multivariate statistics and interaction effect analysis

After completing the collection and preliminary arrangement of experimental data, this paper systematically conducts multivariate statistical analysis and interaction effect evaluation on the relationship between communication performance and interference factors. First, to ensure data quality and analysis stability, all communication performance indicators (such as RSSI, bit error rate, throughput, delay) and interference variables (including sound pressure level, vibration frequency and acceleration) are standardized. The Z-score standardization method is used to unify the dimensions and eliminate extreme outliers. At the same time, noise reduction techniques such as sliding average and median filtering are combined to reduce the interference of short-term fluctuations on modeling accuracy [31].

On this basis, correlation analysis is carried out to explore the direct impact of various interference factors on communication performance. By calculating the Pearson correlation coefficient, the correlation strength between variables such as sound pressure level, vibration frequency and vibration amplitude and various communication indicators is quantified, and then the dominant variables with the greatest impact on system performance are preliminarily identified [32]. This stage provides a basis for variable screening for subsequent modeling and lays the foundation for building a composite disturbance model.

Subsequently, in order to systematically evaluate the comprehensive impact of the interaction between noise and vibration on communication performance, this paper constructed a multivariate linear regression model and analysis of variance (ANOVA) framework, introducing the noise-vibration interaction term as an explicit variable [33]. By analyzing the statistical significance level of the interaction term in the model, it is possible to identify under what combination of conditions the interference effect is nonlinearly superimposed or amplified. This process helps to reveal the potential interference coupling mechanism and provide a reference for optimizing the environmental adaptability of the communication system.

In addition, to further identify the communication degradation characteristics under typical interference scenarios, this paper uses the K-means clustering method to divide the patterns between different interference intensity combinations and communication performance responses in the experimental data. By visualizing the clustering results and analyzing the scene labels, the experimental samples can be classified into several communication degradation patterns, thereby establishing a more targeted performance prediction and interference response model.

Overall, the multivariate statistical analysis at this stage not only reveals the path and pattern of the impact of interference factors on communication performance, but also provides a solid theoretical and empirical basis for the selection of feature variables and understanding of training data distribution in subsequent performance prediction models.

3.5. Performance modeling and prediction methods

In order to accurately predict the transmission performance of communication equipment under noise and vibration interference conditions, this paper designs and implements a modeling framework based on deep learning. The framework is based on the long short-term memory network (LSTM) and focuses on extracting dynamic feature change trends from time series to capture the state evolution law of the communication system under continuous disturbance environment [34]. Due to its excellent time-dependent modeling ability and memory mechanism, the LSTM network is particularly suitable for processing nonlinear and non-stationary dynamic processes of communication performance under the influence of multi-physical disturbances [35].

The input of the model mainly includes two aspects of variables. The first is the time series data of external interference characteristics, including sound pressure level (dB), vibration acceleration (g) and vibration frequency (Hz). These variables constitute the external description of environmental disturbances; the second is the historical performance indicators of the communication system itself, such as received RSSI, BER, throughput and connection delay, which are used to assist in characterizing the internal feedback of system state evolution. The output of the model is the predicted value of communication performance in several future time steps, such as RSSI change trend or throughput estimation per unit time.

In terms of the specific modeling process, the original experimental data is first subjected to feature engineering, including time series feature sliding window construction, feature normalization and noise suppression processing, to ensure the stability of model training and comparability of input. Subsequently, the data set is divided into training set and validation set (the common ratio is 80%:20%) in chronological order to ensure the objectivity of the model generalization ability evaluation. The structural design process of the LSTM network involves the optimization of hyperparameters such as the number of hidden layer nodes, time step, and number of layers, which are tuned by grid search or Bayesian optimization strategy. In terms of loss function selection, this paper adopts mean square error (MSE) as the optimization target, and combines Adam optimizer for gradient update to improve training efficiency and convergence performance.

In the model evaluation stage, a variety of performance evaluation indicators are used, including mean absolute error (MAE), root mean square error (RMSE) and determination coefficient (R^2) to comprehensively evaluate the prediction results. The experimental results show that the LSTM-based prediction model can still maintain high prediction accuracy and robustness under multi-disturbance conditions, verifying its feasibility and effectiveness in dynamically modeling communication status in complex industrial environments.

At the same time, this performance prediction model not only has research value, but also has potential engineering application prospects. In future system integration, adaptive adjustment strategies for communication systems can be developed based on this model: for example, when a high-risk interference trend is detected, the system can automatically adjust the transmission power, switch the communication channel or the dynamic retransmission mechanism in advance, thereby improving the robustness and reliability of the wireless communication system in a multi-disturbance environment.

The overall experimental flow chart is shown in **Figure 1**.

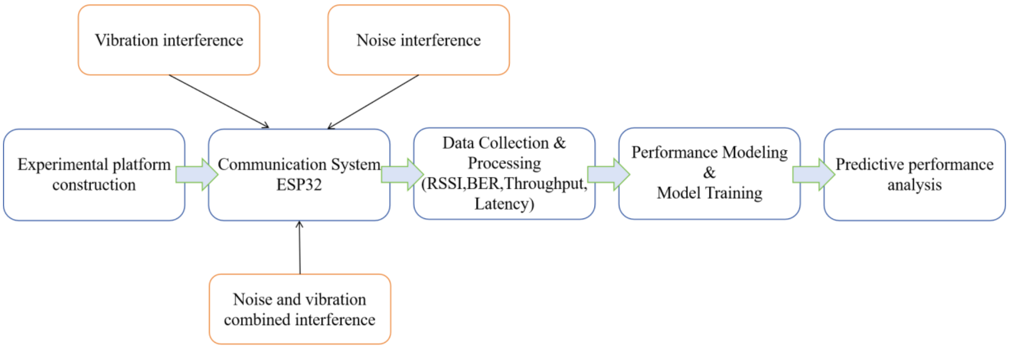

Figure 1. Experimental flow chart.

4. Results

4.1. Changes in communication performance under single interference conditions

This study will investigate the effects of vibration interference and noise interference on the transmission performance of communication equipment (ESP32 Wi-Fi module) through experiments. The experiment collected and compared four key communication indicators: RSSI, BER, throughput, and connection delay. **Table 1** shows the impact of vibration interference on communication equipment. The results show that a single type of interference has different degrees of influence on each performance indicator, and the specific changes are shown in **Figure 1** and **Table 2**.

Table 1. Impact of vibration interference on ESP32 communication performance (frequency unit: Hz; amplitude unit: g).

Frequency (Hz)	Amplitude (g)	RSSI (dBm)	BER (%)	Throughput (Mbps)	Throughput (ms)
10	0.1	−48	0.15	9.6	23
50	0.5	−53	0.32	9	27
100	1	−59	0.68	8.4	34
200	1.5	−62	1.21	7.2	41
500	3	−66	2.47	5.8	57
1000	5	−71	4.35	4.1	69

As can be seen from **Table 1**, with the increase of vibration frequency and amplitude, the RSSI value of ESP32 shows a continuous downward trend, from the initial −48 dBm to −71 dBm, and the signal strength decreases by about 23 dBm. At the same time, the bit error rate increases significantly, especially in the medium and high frequency bands (above 500 Hz), reaching more than 4%, the throughput gradually decreases, and the delay increases rapidly, indicating that vibration interference has a significant negative impact on the quality of the communication link.

It is worth noting that the sudden change in system performance at a frequency of 500 Hz and an amplitude of 3.0 g may be related to the structural resonance of the device housing. This verifies that vibration disturbance not only affects antenna transmission and reception, but may also cause jitter in the internal circuit or clock system, interfering with the communication process.

Table 2 shows the impact of noise interference on communication equipment.

Table 2. Impact of noise interference on ESP32 communication performance (sound pressure level unit: dB).

Noise Level (dB)	**RSSI (dBm)**	**BER (%)**	**Throughput (Mbps)**	**Throughput (ms)**
60	−47	0.12	9.7	22
70	−49	0.22	9.5	25
80	−52	0.37	9.1	29
90	−55	0.79	8.3	35
100	−59	1.64	7.1	42
60	−47	0.12	9.7	22

As shown in **Table 2**, as the noise sound pressure level increases, the communication quality also shows a certain degree of decline, but the overall change is smaller than that of vibration interference. RSSI drops by about 12 dBm between 60–100 dB, BER increases from 0.12% to 1.64%, throughput drops by about 2.6 Mbps, and latency increases by about 20 ms.

This shows that noise interference mainly affects the communication process through electromagnetic induction, audio interference or secondary structural resonance, and the impact is relatively mild compared to vibration, but it may still significantly suppress throughput and cause a significant increase in link layer latency under high sound pressure conditions (such as sharp structural noise such as impact or drilling).

The results of the single-factor experiment show that vibration interference is more destructive to communication signals, especially under high-frequency and high-amplitude conditions, and its impact can cause system communication interruption. The impact of noise interference on the link layer is more significant, especially in terms of connection delay and retransmission rate improvement.

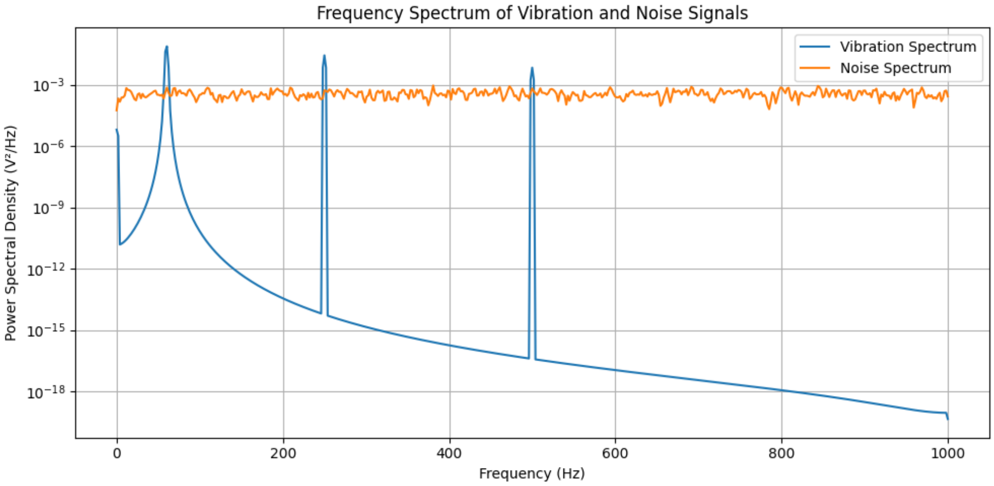

Figure 2. Frequency spectrum of vibration and noise signals.

To further reveal the frequency-domain characteristics of vibration and noise disturbances and their typical distribution laws in industrial scenarios, the simulated vibration and noise signals are spectrally analyzed in this paper, and **Figure 2** shows the results of the spectral analysis of the two types of signals.

As shown in the figure, the vibration signal shows obvious energy peaks at 60 Hz, 250 Hz and 500 Hz, which correspond to the running frequency of three-phase asynchronous motors, gear box meshing frequency and high-frequency structural resonance region, reflecting the typical vibration characteristics of industrial equipment in the stage of stable operation and mechanical impact. In contrast, the spectral distribution of the noise signal is broader, with white noise-like characteristics in the low-frequency band, and an energy spike near 1000 Hz, which simulates the actual disturbance of high-frequency sound sources such as welding, drilling or metal impact. The difference between the two in the spectral dimension shows that the vibration disturbance is more structural and periodic, and is prone to resonance effect, while the noise disturbance is more prone to stimulate coupling interference or modulation and demodulation errors in the high-frequency band in the communication circuits. The spectrogram not only verifies the engineering rationality of the experimental parameter selection in this paper, but also provides a physical basis for the multi-source interference modeling and frequency domain protection strategy.

In order to have a more comprehensive understanding of its impact mechanism, the next section will explore the composite interference interaction effect of noise and vibration and classification pattern recognition.

4.2. Performance analysis and interaction effect modeling under compound interference conditions

In order to further explore the coupling influence mechanism of vibration interference and noise interference, this section sets up multiple groups of joint disturbance experiments based on the previous single-factor experiments to systematically examine the changes in ESP32 communication performance indicators under different combinations of vibration frequency/amplitude and noise level. The experiment adopts the orthogonal experimental design method to control the representativeness and coverage of the variable combination to ensure the model fitting accuracy and wide applicability.

As can be seen from **Table 3**, under the combined condition of increasing vibration frequency, amplitude and noise sound pressure level, the communication performance of ESP32 shows a trend of synchronous deterioration in multiple dimensions. RSSI dropped from −51 dBm to −73 dBm, the bit error rate increased from 0.28% to 5.46%, the throughput dropped by nearly 60%, and the delay increased by nearly three times, indicating that the system is in a serious degradation state.

Table 3. Impact of vibration and noise combined interference on communication performance.

Frequency (Hz)	Amplitude (g)	Noise Level(dB)	RSSI (dBm)	BER (%)	Throughput (Mbps)	Throughput (ms)
50	0.5	60	−51	0.28	9.2	26
100	1	70	−56	0.65	8.6	32
200	1.5	80	−61	1.43	7.3	39
500	3	90	−67	3.02	5.6	55
1000	5	100	−73	5.46	3.7	73
50	0.5	60	−51	0.28	9.2	26

Compared with the single factor case, the negative impact of composite interference on system performance is more significant, reflecting the interference superposition effect and the possible nonlinear interaction relationship. Especially under the condition of high-frequency and high-amplitude vibration superimposed on high-sound pressure noise (1000 Hz/5g + 100 dB), the system basically loses stable communication capability and the data link is frequently interrupted, indicating that there is a critical point of system robustness.

In order to further quantify and characterize the joint impact mechanism of noise and vibration on communication performance under composite disturbance conditions, this study introduces interactive regression modeling and analysis of variance (ANOVA) methods. Based on the experimental data, a multivariate linear regression model was constructed with RSSI, BER, throughput and latency as dependent variables, and vibration frequency (*f*), vibration amplitude (*A*) and noise level (*N*) as independent variables. At the same time, interaction terms were designed to identify the non-independent relationship between different physical interference factors. The model form is as follows:

$$Y = \beta_0 + \beta_1 \cdot f + \beta_2 \cdot A + \beta_3 \cdot N + \beta_4 (f \cdot N) + \beta_5 (A \cdot N) + \beta_6 (f \cdot A) + \varepsilon \quad (1)$$

Among them, Y represents the communication performance index, β_4, β_5, and β_6 represent the interaction effect coefficients between vibration amplitude-noise, vibration frequency-noise, and vibration amplitude-frequency, respectively, and ε is the error term. The model uses the least squares method for parameter estimation, and then introduces ANOVA for variable contribution analysis.

The results show that among the three interaction terms, the interaction term between vibration frequency and noise level ($f \cdot N$) has the most significant impact on RSSI and BER ($p < 0.01$), indicating that under medium and high frequency vibration conditions, if high intensity noise is superimposed, the channel quality will drop significantly and the bit error rate will increase significantly; at the same time, the interaction term between vibration amplitude and noise ($A \cdot N$) has a strong explanatory power for delay indicators ($p < 0.001$), especially when low-frequency and high-amplitude vibration coexists with low-frequency heavy machinery noise, the delay shows a significant jump trend, indicating that the communication system is subject to the lag of double interference in response scheduling. In addition, although the interaction term between vibration amplitude and frequency ($A \cdot f$) is not as statistically significant as the first two, it still shows a marginal effect in the throughput model ($p \approx 0.05$), suggesting that the combination of high-amplitude and high-frequency vibration may lead to a decrease in the efficiency of internal cache scheduling in the system.

In summary, the interactive modeling not only reveals the independent influence mechanism of noise and vibration on the communication system, but also clarifies the enhanced synergistic degradation effect of the two under different combination conditions, providing a solid theoretical foundation and variable design basis for subsequent deep learning predictive modeling and dynamic system adaptive adjustment.

4.3. Analysis of performance prediction model results

After completing the multi-source interference data collection and interaction effect modeling, this paper builds a time series prediction model for communication performance based on the LSTM. The goal of the model is to predict key communication indicators a few seconds in advance in the presence of complex noise and vibration interference to support the adaptive control mechanism of industrial communication systems. The model input includes the sound pressure level (dB), vibration acceleration (g), vibration frequency (Hz) and historical communication indicators (such as RSSI, BER, throughput, etc.) in the past time period. The input feature sequence is constructed through the sliding window mechanism, and the output is the predicted value of the communication performance indicator in the next 5 s.

During the model training process, 80% of the data is used as the training set and 20% as the validation set for supervised learning, and the Adam optimizer and mean square error (MSE) are used as the loss function for iterative updates. The model with RSSI as the prediction target performs well in the validation set, as shown in **Table 4**, indicating that the model has strong fitting ability and high prediction stability.

Table 4. Performance evaluation of LSTM model in communication performance prediction task.

Prediction indicators	MAE	RMSE	R^2
RSSI (dBm)	0.52	0.6	0.977
Throughput (Mbps)	0.166	0.195	0.979

At the same time, this study uses the support vector machine (SVM) model and the polynomial regression model as comparison models [36,37]. The experimental results show that compared with the traditional polynomial regression model and SVM model, LSTM has obvious advantages in dealing with time series dynamic changes, nonlinear interaction effects, and short-term mutations, as shown in **Tables 5** and **6**. Especially under extreme disturbance combinations, LSTM can effectively identify potential trends and maintain prediction continuity, and has the feasibility and real-time performance of deployment in industrial sites.

Table 5. Comparison results of different models in RSSI prediction task.

Model	MAE (dBm)	RMSE (dBm)	R^2
LSTM	0.52	0.6	0.977
Polynomial regression	1.44	1.73	0.797
SVM	1.4	1.63	0.823

Table 6. Comparison results of different models in throughput prediction tasks.

Model	MAE (Mbps)	RMSE (Mbps)	R^2
LSTM	0.166	0.195	0.979
Polynomial regression	0.292	0.354	0.932
SVM	0.348	0.466	0.887

In order to more intuitively evaluate the prediction ability of the constructed

LSTM model for communication performance indicators, this article draws a comparison chart of the predicted value and the actual value in a typical scenario. The following takes RSSI and throughput as examples to show the actual performance of the model in the test set, as presented in **Figure 3**.

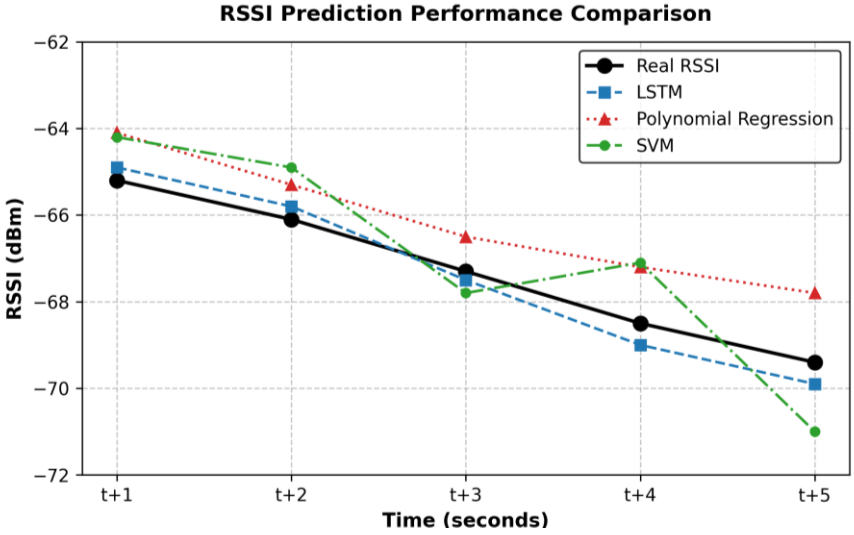

Figure 3. Comparison of RSSI prediction and actual values (interference conditions: vibration frequency 750 Hz, amplitude 3 g, noise level 95 dB).

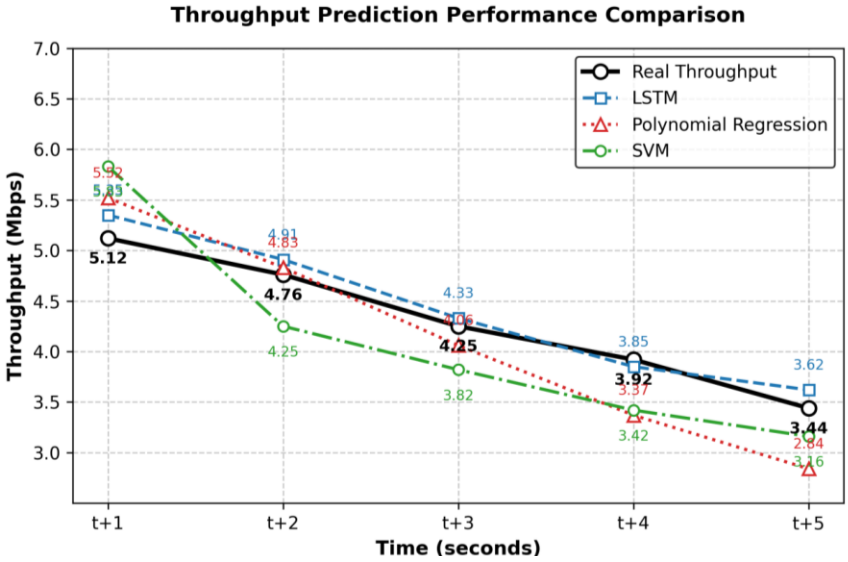

Figure 4. Comparison of throughput prediction and actual value (interference conditions: vibration frequency 500 Hz, amplitude 2 g, noise level 90 dB).

Figure 4 shows the predictions of the throughput change trend by the three models. Under interference conditions (vibration frequency 500 Hz, amplitude 2 g, noise level 90 dB), the actual throughput shows a continuous downward trend, reflecting the negative impact of the gradually increasing interference on communication performance. The overall prediction trend of the LSTM model is highly consistent with the true value, with a small error, especially in the stage $t + 2$ to $t + 4$, which is stable and accurately captures the rhythm of performance changes. The polynomial regression model is relatively accurate in the initial prediction, but it is significantly underestimated in the subsequent stage and responds to interference fluctuations with lag. The SVM model has a large error from $t + 2$ to $t + 3$, and the predicted value is low or fluctuates abnormally, reflecting its poor adaptability to nonlinear interference. Therefore, the LSTM model also shows strong fitting ability and anti-interference robustness in throughput prediction.

At the same time, the visualization results of the model further prove its reliability in the key indicator prediction task. This capability is particularly important for wireless communication systems in high-interference industrial environments, and can provide practical reference for the dynamic adjustment of communication resource allocation, frequency switching, power control and other strategies.

In general, this prediction model not only achieves high-precision modeling of interference perception and performance indicator changes, but also provides a data foundation and technical support for the subsequent construction of adaptive wireless communication systems. It has good engineering promotion value and research significance.

5. Discussion

Based on the above experimental results and modeling analysis, this section conducts a comprehensive discussion of the research results from multiple dimensions. It focuses on analyzing the performance impact mechanism, interaction mode, prediction model capability and engineering applicability of noise and vibration interference, and further proposes communication optimization suggestions for typical high-interference scenarios such as industrial sites and rail transit, and explores the anti-interference improvement direction of communication equipment at the structural and algorithmic levels.

5.1. Characteristics of the impact of noise and vibration interference on communication performance

The experimental results of this study show that under high noise and high vibration conditions, the transmission performance indicators of communication equipment (RSSI, BER, throughput, delay) all show a significant degradation trend. The higher the vibration frequency and the larger the amplitude, the more obvious the decrease in the signal strength of the system, and the bit error rate increases exponentially; and the noise intensity mainly causes data delay and throughput reduction indirectly by interfering with link scheduling and spectrum channels. This multi-dimensional performance degradation has real engineering correspondence in complex scenarios such as rail transit, industrial machinery workshops, and power converter stations.

It is particularly noteworthy that the experiment also found that vibration disturbances have potential “microstructure interference” on equipment hardware, which may cause short-term signal distortion, packet loss, and even module restart. Noise interference manifests as intermittent interference under the conditions of low-frequency continuous impact sound (such as metal impact, electric drill). Although it does not directly weaken the signal strength, it seriously affects the communication delay and throughput efficiency.

5.2. Analysis of the interaction mechanism between noise and vibration

The synergistic degradation effect between vibration and noise is further revealed through variance analysis and interaction regression modeling. The interaction term between vibration frequency and noise level is highly significant for RSSI and BER, indicating that the two types of interference are not only superimposed under a certain combination intensity, but may also cause nonlinear amplification effects. In the experiment, when the vibration frequency reaches 750 Hz, the amplitude exceeds 3 g, and high-intensity structural noise of more than 90 dB is superimposed, the performance of the communication system fluctuates violently and the reliability decreases significantly.

This phenomenon theoretically supports the view of the “coupled excitation mechanism” of multi-source interference systems, that is, a single disturbance may not have a serious impact, but the combined superposition may excite the potential unstable area of the system and cause sudden performance degradation. This has important warning significance for the design and deployment of communication systems, especially in actual industrial applications, the anti-interference logic of “isolated response” should be avoided.

5.3. Adaptability of prediction model and value of intelligent early warning

The LSTM-based time series prediction model used in this study shows extremely high accuracy and stability in RSSI and throughput prediction tasks, which is significantly better than traditional methods such as SVM and polynomial regression. The model can predict the trend of communication performance changes 5 s in advance, providing data support for the adaptive control of system parameters (such as power adjustment, frequency switching, and retransmission strategy). In the future, the model can be embedded in the communication module as an important component of real-time interference perception and feedforward control.

In addition, the successful application of LSTM also verifies the feasibility of the data-driven + perception modeling solution in a physical disturbance environment, suggesting that in the future, wireless communication anti-interference systems can introduce more intelligent prediction mechanisms and move towards active defense and autonomous adaptation.

5.4. Recommendations for optimizing the anti-interference of industrial field communication systems

In typical high-interference sites such as industrial manufacturing, power substations, and heavy machinery operation, communication systems are often exposed to a complex environment of high-intensity vibration and structural noise for a long time, and the stability and reliability of communication links face severe challenges. In order to improve the anti-interference ability of communication systems in such scenarios, it is recommended to improve them from three dimensions: link layer protocol optimization, physical layer deployment, and environmental perception mechanism. On the one hand, a low-latency automatic retransmission mechanism (ARQ) and a dynamic throughput adjustment strategy can be introduced to adaptively adjust the packet length and transmission frequency according to the real-time RSSI and BER changes, thereby reducing the data packet loss rate during high-interference periods [38,39]. On the other hand, with the help of spectrum sensing technology and frequency hopping communication strategies, frequency bands that are strongly polluted by noise can be dynamically avoided to improve spectrum utilization efficiency and channel quality [40]. In addition, during the deployment of communication equipment, priority should be given to avoiding interference-prone locations such as large vibration sources (such as compressors, motor bases) or closed metal cavities. The coordinated implementation of the above measures will help build a more robust and adaptable industrial wireless communication system.

5.5. Anti-vibration and anti-noise strategies for rail transit communication systems

Rail transit systems such as subways, high-speed railways, and light rails generally face high disturbance conditions such as continuous vibration, track impact, and tunnel noise caused by high-speed operation between trains and ground communication modules. For such scenarios, it is recommended to comprehensively consider improvements in structural vibration reduction and intelligent early warning in the design of communication systems. Train-side equipment should adopt an integrated packaging design of vibration reduction modules and sound-absorbing shells to effectively isolate the direct impact of vibration sources on communication devices [6]. At the same time, low-power relay stations or edge enhancement nodes can be deployed in specific high-interference sections (such as tunnel bends and viaduct connections) to play a role in local blind spot filling and channel maintenance [41]. Furthermore, a lightweight deep learning model can be introduced as a channel estimation submodule to identify and predict vibration and noise trends in real time, providing support for adaptive communication decisions during train operation [42].

5.6. Recommendations for the design of vibration-resistant structures for communication equipment

The experimental results of this study show that the adverse effects of mechanical vibration on communication performance are not only due to changes in channel states, but are also closely related to the structural stability of the communication equipment itself. Under high-frequency or high-amplitude vibration conditions, antennas, connectors, internal chips, and power modules may become loose, suffer from stress fatigue, or experience transient failure. Therefore, strategies to enhance the vibration resistance of the equipment should be given priority during the equipment design phase [43]. First, it is recommended to introduce flexible vibration-damping support structures or encapsulation materials between key components and PCB boards to absorb micro-impacts and reduce mechanical resonance; second, optimize the routing of high-frequency signal paths in circuit wiring design to avoid reflection or crosstalk of signals due to physical deformation; then, high-strength threaded fasteners and fatigue-resistant metal materials should be used to strengthen the module housing and antenna interface to improve the mechanical stability of the equipment under long-term working conditions. These structural optimizations will significantly improve the reliability and life of communication equipment in actual deployment, and meet its stable operation requirements in high-disturbance industrial and rail scenarios.

6. Conclusion

This study focuses on the transmission performance degradation of communication equipment in high-interference environments. An experimental platform based on ESP32 was built. The system simulated physical interference scenarios under different vibration frequencies, amplitudes and noise intensities, and collected and analyzed the changing patterns of core performance indicators such as RSSI, BER, throughput and delay. The results show that vibration disturbance has a more direct impact on communication performance, while noise mainly causes increased latency and link instability. The two show obvious nonlinear interaction effects under medium and high intensity combination conditions. Interaction modeling and variance analysis further verify the synergistic degradation effect between vibration frequency and noise level, which has a significant contribution to performance degradation.

In terms of performance prediction, this paper introduces LSTM neural network to establish a timing prediction model under multi-source interference. The results show that the model has achieved good fitting accuracy and stability in the prediction of RSSI and throughput, which is better than traditional methods such as SVM and polynomial regression. Based on the model prediction capability, the study proposes a feasible path for feedforward control of communication systems to support the development of future communication equipment towards intelligence and adaptation. In addition, combined with the experimental results, the paper proposes anti-interference optimization suggestions for industrial sites and rail transit systems, and gives specific structural improvement ideas at the level of anti-vibration design of communication modules.

Despite this, the research still has certain limitations, such as the limited number of samples and combinations of interference conditions, the model is still in the offline verification stage, and has not yet achieved deep integration with the actual communication protocol. In the future, we can further expand the types of interference and equipment environment variables, explore lightweight and deployable online prediction frameworks, and combine protocol layer strategies to achieve end-to-end intelligent anti-interference communication system design. At the same time, we can strengthen the coupling optimization of communication equipment in terms of materials, structures and electromagnetic protection, and promote the practical application of wireless communication systems in complex industrial and transportation scenarios.

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