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Research on anti-jamming transmission mechanism and intelligent modulation recognition algorithm of data link for complex battlefield environment

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Abstract: Under the background of multi-domain joint operations in modern warfare, data link, as the "nerve center" of the battlefield, faces the severe challenge of high-density and multi-dimensional dynamic electromagnetic interference. The traditional data link system has an "adaptive dilemma" because it adopts a fixed anti-jamming strategy, and modulation recognition is limited by the performance bottleneck under low signal-to-noise ratio (SNR) and the "intelligent bottleneck" of insufficient generalization ability of deep learning model. Aiming at the above problems, this study constructs a closed-loop framework of "perception-decision-execution", and proposes a cross-layer cooperative anti-interference transmission mechanism and an intelligent modulation recognition algorithm. The anti-jamming transmission mechanism perceives the channel and interference characteristics in real time through lightweight convolutional neural network (CNN), and dynamically optimizes frequency hopping, direct sequence spread spectrum and power control strategies based on Dueling Double DQN (DDQN) algorithm to realize adaptive resource allocation. The design of the intelligent modulation recognition algorithm TFSC-Net (Time-Frequency-Symbolic Joint Network) dual-channel feature fusion model jointly extracts features from the time-frequency domain and symbol domain of the signal, and improves the recognition accuracy and generalization capability under low SNR by combining an enhanced loss function. Experimental results demonstrate that the proposed scheme achieves a low bit error rate of 8.7×10^{-5} and a throughput of 34.9 Mbps in a strong interference environment (JSR=20dB). TFSC-Net achieves a recognition rate of 89.4% at 0dB SNR and 97.3% at 10dB SNR, with a latency controlled at 13.8ms, balancing interference resistance, recognition accuracy, and real-time performance. The research findings provide technical support for enhancing the survivability of battlefield communications, strengthening electronic warfare advantages, and promoting the development of the next-generation data link system.

1. Introduction

Modern warfare has entered the era of "multi-domain joint operations". As a key "nerve center", data link connects command and control, intelligence reconnaissance and weapon platform, and its reliability is very important for battlefield situation awareness and decision-making efficiency. In the future, the combat environment will face the challenge of highly dense, multidimensional and dynamic electromagnetic interference, including hundreds of intentional or unintentional interference sources, diverse interference types and complex channel characteristics. Faced with such a challenge, the traditional data link system can't adapt to the increasingly complex and dynamic "jamming-anti-jamming" battlefield demand because of the fixed anti-jamming strategy.

At present, data link communication faces two core challenges: first, the "adaptive dilemma" of anti-jamming transmission. The existing technologies, such as FHSS and direct sequence spread spectrum (DSSS), rely on fixed channel models and do not perform well in unknown or time-varying interference scenarios. For example, traditional frequency hopping systems are easily tracked under smart interference, which leads to communication interruption [1]; Although multi-technology fusion can enhance the anti-jamming ability, the computational complexity is greatly increased, which is difficult to meet the real-time requirements of tactical edge nodes [2]. Secondly, it is the "intelligent bottleneck" of modulation recognition. In the dynamic battlefield environment, many modulation methods and parameters change in real time, which makes the recognition rate of traditional feature extraction methods lower than 60% under the condition of low signal-to-noise ratio (SNR). Although the deep learning model performs well on public data sets, its generalization ability in the actual battlefield is limited due to the significant differences between training and testing environments [3-4].

Based on environmental awareness, dynamic decision-making and intelligent processing, this study puts forward a solution to the challenge of data link communication, which has three military values: improving the battlefield survivability, ensuring the transmission of key information under strong interference through dynamic anti-jamming strategies, and supporting the closed loop of operations; Enhance the advantages of electronic warfare, analyze enemy parameters in real time with the help of intelligent modulation identification, and assist in the allocation of jamming resources; Promote the paradigm transformation of communication technology and build a new generation of data link system that is "cognitive-driven and actively adaptive". Compared with the existing work, the research innovation is embodied in: cross-layer collaborative design, deep integration of anti-interference and identification, and reduction of processing delay; Dynamic intelligent optimization, which combines reinforcement learning (RL) and lightweight neural network to realize strategy adaptation and real-time reasoning; And through the software-defined radio (SDR) platform in a typical battlefield environment to carry out practical verification.

2. Design of anti-jamming transmission mechanism

Construct a closed-loop framework of "perception-decision-execution" to realize dynamic anti-jamming communication. Through real-time perception of channel state and extraction of interference characteristics, combined with RL technology to optimize resource allocation and drive adaptive transmission strategy [5]. This mechanism breaks through the traditional fixed anti-jamming mode and improves the robustness and flexibility of the system in complex electromagnetic environment.

The system is divided into three layers as shown in Figure 1. In the environmental perception layer, lightweight convolutional neural network (CNN) is used to identify the type and intensity of interference. The strategy decision layer realizes the dynamic optimization of anti-jamming strategy based on Dueling Double DQN (DDQN) algorithm [6]; The transmission execution layer performs communication by means of adaptive combined frequency hopping (FH), DSSS and power control [7]. The overall design gives consideration to both performance and real-time, and meets the low delay requirements of tactical edge nodes.

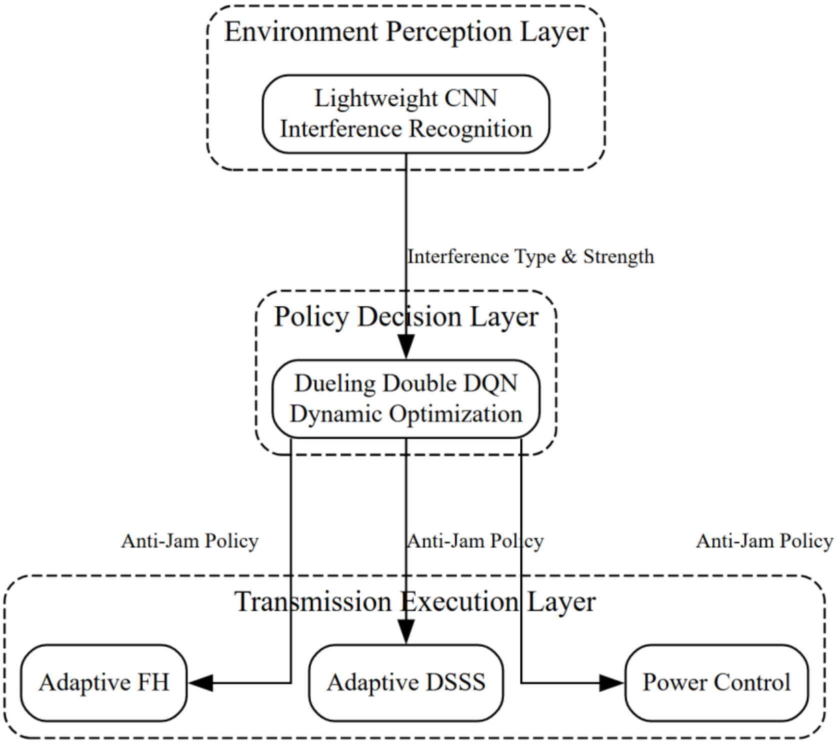

Figure 1 System structure

The model aims at maximizing the utility function, comprehensively considers the communication rate, energy consumption and transmission delay, and optimizes the combination of frequency hopping pattern, transmission power and modulation bandwidth. In the decision-making process, the system selects the optimal transmission parameters according to the interference type, SNR and node residual energy input by the sensing layer. The design of reward function takes into account the transmission success rate, bit error rate requirements and power consumption control, and adopts lightweight DDQN network to realize millisecond-level strategy reasoning to ensure the response speed and adaptability of the system.

3. Research on intelligent modulation recognition algorithm

Aiming at the challenges of diverse modulation methods, low SNR and high real-time recognition in dynamic battlefield environment, this study proposes an efficient intelligent modulation recognition algorithm. The core of the design is to build a "dual-channel feature fusion model", which can simultaneously mine the time-frequency domain and symbol domain features of signals and improve the recognition accuracy under complex interference and SNR conditions. The algorithm can recognize 16 typical military modulation modes such as QPSK, 16QAM, LFM, etc. with SNR not less than 0dB, and the recognition delay is controlled within 20ms, which meets the real-time requirements of tactical communication systems [8].

The proposed model is named TFSC-Net (Time-Frequency-Symbolic Joint Network), and the dual-channel structure is used to process the signal characteristics of different domains respectively (Figure 2). The first branch is a time-frequency feature extraction branch, and the input is the short-time Fourier transform (STFT) spectrogram of I/Q signal. The spectral structure features are extracted through a three-layer two-dimensional convolution network (Conv2D, the number of channels is 32, 64 and 128 in turn), and the spatial attention module is introduced to enhance the recognition ability of key areas. The second branch is the symbol feature branch, which takes as input the instantaneous amplitude and phase difference features ($\Delta A_k, \Delta\varphi_k$) of the signal. The statistical characteristics of the symbol sequence are extracted through a one-dimensional convolutional network (Conv1D, channel number 64 → 128) [9]. Finally, the features of the two branches are concatenated in the fusion layer, and after modeling the temporal dependencies through a bidirectional gated recurrent unit (GRU), they are fed into a Softmax classifier to complete the recognition of modulation types.

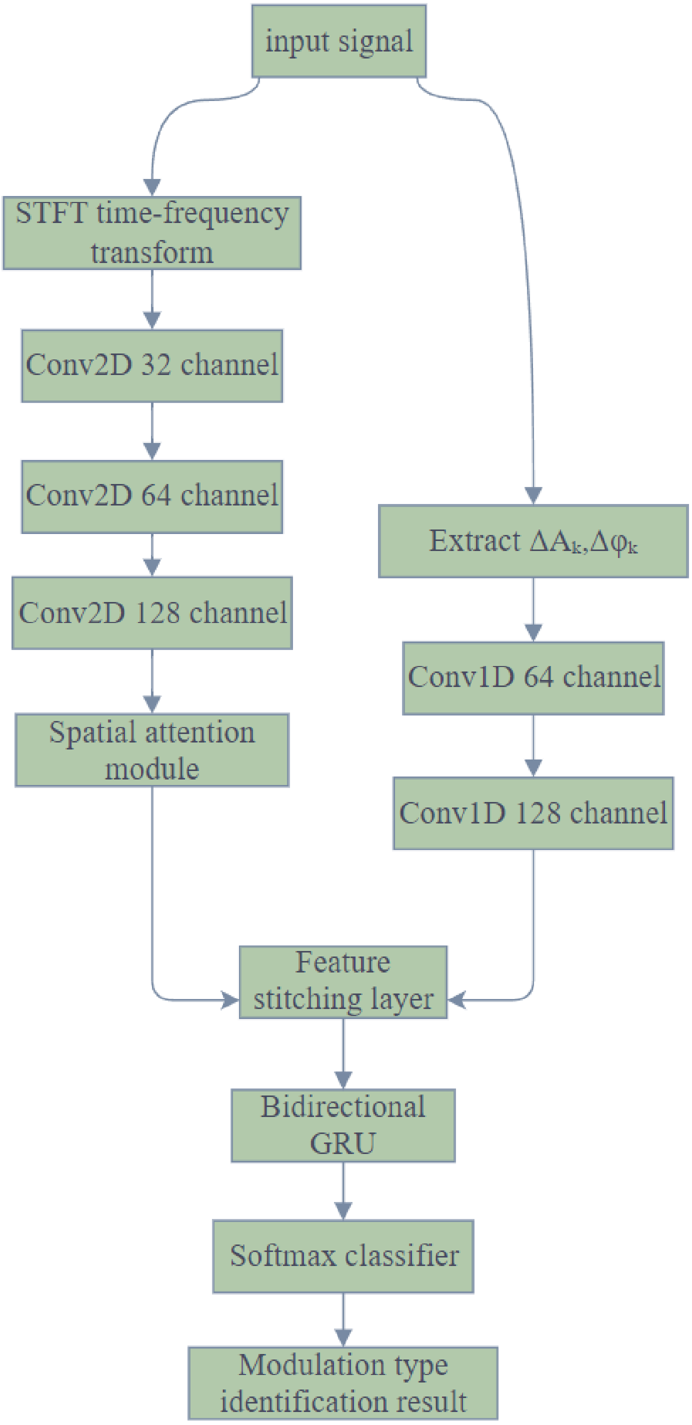

Figure 2 TFSC-Net network structure

Instantaneous amplitude/phase difference of input signal:

$$\varDelta A_k = |A_k - A_{k-1}|, \varDelta \varDelta_k = |\varphi_k - \varphi_{k-1}| \quad (1)$$

In order to improve the generalization ability of the model in unbalanced data sets and complex electromagnetic environment, the traditional cross entropy loss function is improved. Category weight w_i is introduced into the loss function to balance the distribution differences of different modulation methods in the training data, and L2 regularization term is added to suppress over-fitting, and regularization coefficient β is set to 0.001.

$$L = -\sum_{i=1}^{M} w_i y_i \log(\hat{y}_i) + \beta \|\theta\|_2^2 \quad (2)$$

Where M is the number of modulation classes (M =16 in this system). This optimization strategy effectively improves the recognition stability and accuracy of the model under the conditions of SNR and strong interference, and provides reliable technical support for signal intelligent perception and electronic countermeasures in battlefield environment.

4. Experimental verification and result analysis

The experiment is based on a high-performance SDR platform. Four USRP N321 devices are used to build communication nodes. The working frequency band is 2.4GHz, and the system bandwidth reaches 40MHz, which can support real-time verification of various modulation and anti-jamming technologies. The interference source is simulated by three AWG70002 arbitrary waveform generators, which generate narrow-band swept frequency, wide-band noise and pulse interference respectively, and simulate the complex and changeable electromagnetic environment in the real battlefield. The channel condition adopts the urban multipath fading model, and the delay spread is set to 500ns, and the Doppler frequency shift range is ±120Hz, which is closer to the propagation characteristics in the actual combat scene.

Multiple dynamic interference scenarios were designed in the experiment to evaluate the robustness of the proposed anti-interference and recognition algorithm. Specifically, it includes: 2-channel narrowband sweep interference, switching frequency points every 5 seconds, and varying Jamming-to-Signal Ratio (JSR) between 10-20dB; 1 channel of persistent broadband noise interference, with a JSR of 15dB; and 3 channels of random pulse interference, with a JSR range of 8-25dB and pulse width randomly varying between 1-20ms.

Table 1 Anti-jamming performance verification

Plan	BER at JSR=10dB	BER at JSR=20dB	Throughput (Mbps)
Baseline 1 (static)	3.2×10^{-3}	1.8×10^{-2}	18.7
Baseline 2 (no recognition)	7.5×10^{-4}	6.1×10^{-3}	26.3
This scheme	2.4×10^{-5}	8.7×10^{-5}	34.9

Three anti-jamming schemes are compared: Baseline 1 adopts static anti-jamming strategy of fixed frequency hopping and spread spectrum technology, Baseline 2 is RL anti-jamming method without modulation recognition support, and this scheme combines cross-layer cooperation mechanism, combined with RL dynamic anti-jamming and TFSC-Net intelligent modulation recognition. Table 1 shows that when the JSR is 10dB, the bit error rate (BER) of this scheme is as low as 2.4×10^{-5}, significantly better than Baseline 1 (3.2×10^{-3}) and Baseline 2 (7.5×10^{-4}); When the JSR is increased to 20dB, the BER of this scheme still remains at 8.7×10^{-5}, far lower than the 1.8×10^{-2} and 6.1×10^{-3} of the other two. At the same time, the throughput achieved by this scheme reaches 34.9Mbps, significantly higher than the 18.7Mbps of Baseline 1 and the 26.3Mbps of Baseline 2, fully reflecting its better communication performance and transmission efficiency in strong interference environments.

The modulation recognition performance test is based on 8000 sample data sets (500 samples in each class, SNR range is -5~20dB) containing 16 kinds of military modulation signals, such as QPSK, 16QAM, LFM, Barker code, etc., and the recognition accuracy and time delay performance of different algorithms are evaluated under SNR conditions. The experimental results in Table 2 show that the recognition accuracy of the traditional high-order cumulant method is 48.2% and 76.5% when SNR is 0 dB and 10dB, respectively, and the recognition delay is only 1.2ms, but the overall accuracy is low. The accuracy of ResNet-18 is improved obviously, reaching 67.3% when SNR=0dB, and 89.1% when SNR=10dB, but the time delay is increased to 22.6ms; However, TFSC-Net proposed in this study is significantly superior to both of them in accuracy. The recognition rate reaches 89.4% when SNR=0dB, and reaches 97.3% when SNR=10dB. The recognition delay is 13.8ms, which gives consideration to both high accuracy and real-time, and shows stronger battlefield adaptability.

Table 2 Comparison of recognition accuracy

Algorithm	SNR=0dB accuracy	SNR=10dB accuracy	Time delay (ms)
Higher-order cumulant method	48.2%	76.5%	1.2
ResNet-18	67.3%	89.1%	22.6
TFSC-Net(our)	89.4%	97.3%	13.8

5. Conclusion

Aiming at the two core challenges of anti-jamming transmission "adaptive dilemma" and modulation identification "intelligent bottleneck" faced by data link communication in modern war, a set of innovative solutions is proposed. By constructing a "perception-decision-execution" closed-loop framework, dynamic anti-jamming communication is realized, which significantly improves the robustness and flexibility of the system in complex electromagnetic environment. At the same time, TFSC-Net intelligent modulation recognition algorithm is designed, which effectively solves the recognition problem under the condition of low SNR and improves the recognition accuracy and real-time performance. The experimental results show that this scheme shows better communication performance and transmission efficiency in strong interference environment, with significantly reduced BER and greatly improved throughput. In addition, TFSC-Net's recognition rate reaches 89.4% when SNR=0dB, and reaches 97.3% when SNR=10dB, and the recognition delay is controlled within 13.8ms, which fully demonstrates its battlefield adaptability. This study provides important theoretical and technical support for improving battlefield survivability, enhancing the advantages of electronic warfare and promoting the paradigm transformation of communication technology.

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