Design of Airborne Data Link Communication System Based on IP/Non-IP Dual Stack

Wenjing Yang
The 10th Research Institute of CETC, Chengdu, Sichuan, China

Abstract: Aiming at the problem of information silos induced by protocol heterogeneity in airborne data links, this paper designs an airborne data link communication system supporting IP/Non-IP dual-stack communication. Through core technologies including dynamic protocol conversion and routing optimization, the system achieves efficient interconnection between legacy systems and next-generation networks. Experimental tests verify that the system performs excellently in terms of protocol switching latency and data throughput, which significantly improves the real-time performance and compatibility of airborne communication, and provides robust technical support for the integration of future avionics systems.

Keywords: IP/Non-IP Dual Stack; Airborne Data Link Communication System; Design

1. Introduction

With the continuous improvement of the informatization level of avionics systems, airborne data link communication is confronted with a complex scenario where legacy systems and new-generation networks coexist. The traditional Non-Internet Protocol (Non-IP) data link [1] still dominates specific fields, while IP-based networked communication has become an inevitable development trend. The protocol heterogeneity between the two results in difficulties in data interaction, which seriously restricts the efficiency of cooperative operations. In response to this issue, this paper proposes a design of an airborne data link communication system supporting IP/Non-IP dual stack communication. By constructing a dual stack architecture, transparent transmission and intelligent conversion of signals with different standards are achieved. This system aims to solve the problem of heterogeneous network interconnection, comprehensively enhance the adaptability of the data link in complex electromagnetic environments, and provide a scientific basis for the upgrading of airborne communication systems [2].

2. Demand Analysis of Airborne Data Link Communication System

2.1 Functional Demand Analysis

The main functional requirements of the airborne data link communication system supporting IP/Non-IP dual stack communication are as follows: First, the system shall be capable of accessing both IP and Non-IP signals simultaneously and implementing parallel processing via the dual stack; second, it shall possess strong protocol conversion capability to analyze data frames of different standards and accurately map them to the target network, ensuring lossless information semantics; third, the system should be equipped with a dynamic routing management function, which utilizes a link state sensing algorithm to intelligently select the optimal transmission path, ensuring timely response and data exchange among communication nodes. Notably, all functional modules need to cooperate collaboratively to form a closed-loop communication system, thereby successfully breaking the information island [3].

2.2 Performance Demand Analysis

The main performance requirements of the airborne data link communication system supporting IP/Non-IP dual stack communication are as follows: First, the system must achieve high protocol conversion efficiency, accurately handle minor differences in data packets, and ensure a conversion accuracy of over 99%; second, it needs to respond quickly to protocol switching requests, with the time delay from link change detection to the completion of dual stack switching not exceeding 50 ms to meet the real-time requirements of airborne communication; third, the system shall have strong concurrent processing capability, enabling it to process signal data from multiple sensors in a short period and maintain stable and efficient operation even under high-load conditions; fourth, it should feature good scalability, allowing flexible expansion of stack instances and data processing capabilities with the increase in the number of communication nodes to ensure long-term stable operation.

3. Design of Airborne Data Link Communication System Based on IP/Non-IP Dual Stack

3.1 Software Design

3.1.1 Design of dual stack management module

In the airborne data link communication system supporting IP/Non-IP dual stack communication, the dual stack management module is responsible for the efficient and real-time scheduling of resources for different stacks. To ensure the system's compatibility range and signal processing accuracy, a modular operating system kernel is adopted, combined with a high-performance protocol conversion engine. Each stack instance is configured with independent memory space and interrupt vectors, effectively supporting both IP and Non-IP networks and ensuring low-latency and stable data transmission from the access layer to the application layer. The manager collects signals according to the characteristics of different data streams and initially analyzes and preprocesses data frames through advanced scheduling algorithms for subsequent processing. This design achieves full-protocol coverage of airborne data link communication signals, ensures stable monitoring and forwarding in various transmission environments, and provides a unified interface for upper-layer applications [4].

3.1.2 Design of dynamic routing and forwarding module

The system first uses technologies such as link quality evaluation and delay analysis to decompose the network into multiple logical domains and extract key information, including bandwidth utilization, packet loss rate, and changes in node load. To enhance the system's adaptability in complex electromagnetic environments, this paper introduces an adaptive routing algorithm based on the Optimized Link State Routing (OLSR) protocol. This algorithm reduces the overhead of control message flooding through a multi-point relay mechanism and dynamically eliminates congested links and high packet loss paths based on link quality metrics, thereby improving the data packet delivery rate under weak signal conditions. The dynamic routing and forwarding module adopts a Long Short-Term Memory (LSTM) network to analyze the above time-series characteristics, and real-time identifies abnormal patterns in the network within a 50 ms time window, such as link interruption, narrowband interference, or sudden drop in signal-to-noise ratio caused by multipath fading. Through precomputed backup paths and a fast routing convergence mechanism (convergence time < 100 ms), it quickly responds to abnormal working conditions and ensures the continuity of the data link communication link.

3.1.3 Design of security encryption and authentication module

The goal of the security encryption and authentication module is to address security vulnerabilities caused by protocol differences in a multi-protocol environment and comprehensively improve the integrity of data transmission. To this end, this paper adopts the national secret SM4 block cipher algorithm as the core encryption engine, combined with the SM3 hash algorithm for integrity verification, to construct a dynamic authentication framework based on timestamp synchronization and sliding window mechanism. Aiming at the time sequence mismatch problem caused by the difference in data frame processing delay between different stacks (IP and Non-IP), the IEEE 1588v2 Precision Time Protocol is introduced to synchronize the clocks of each node, and a dynamic adjustment model based on time difference compensation is established. By real-time measuring the time deviation between the data frame encapsulation timestamp and the encryption engine completion timestamp, the encryption compensation factor is dynamically calculated, and the key update cycle and authentication challenge-response time window are adjusted. Simultaneously, the correlation between the arrival phase of data frames and the output phase of the key generator is analyzed, and a dynamic synchronization function based on weighted moving average is constructed to ensure the continuity of the output of the key derivation function when switching between different stacks [5].

3.2 Hardware Design

To ensure high sensitivity and wide-area coverage of the system, the hardware platform selects the Xilinx Zynq UltraScale+ MPSoC series embedded processing platform (model XCZU7EV), which integrates a quad-core ARM Cortex-A53 application processor, a dual-core Cortex-R5 real-time processor, and FPGA programmable logic units, supporting a multi-core heterogeneous parallel processing architecture. It is suitable for the real-time reception and parsing of various signal protocols (ARINC 429, MIL-STD-1553, Ethernet, RS-422) [6]. The device is equipped with a built-in 16-channel parallel Analog-to-Digital Converter (ADC, Analog Devices AD9680) with a sampling rate of 1 GSPS and a resolution of 14 bits, which can simultaneously receive baseband signals from different data link radio frequency front-ends and transmit IQ sampling data to the processing unit through the AXI-4 high-speed bus [7]. In terms of network transmission, the system selects the Moxa EDS-510A series industrial-grade Layer 3 switch, which supports gigabit fiber interfaces and IEEE 802.1Q VLAN division, ensuring that the data transmission rate from the signal receiving device to the data processing server is not less than 800 Mbps, and the end-to-end transmission jitter is controlled within 10 μs [8]. The processor is equipped with 16 GB DDR4 memory and 512 GB NVMe solid-state storage, with a fixed-point computing power of more than 1.2 TOPS (for FPGA logic units), which can efficiently complete channel decoding, demodulation, and protocol parsing [9]. The hardware architecture design fully considers the temperature, vibration, and electromagnetic compatibility requirements in the airborne environment, provides a deterministic operation base for the software system, and ensures the efficient and stable operation of the airborne data link communication system under the full mission profile [10].

4. System Experimental Testing

4.1 Experimental Platform Setup

To comprehensively evaluate the performance of the system proposed in this paper under different environmental conditions, an empirical test platform simulating the airborne communication environment is built. The environment includes 5 distributed communication nodes, evenly deployed in different geographical areas, and each node is equipped with the above-mentioned receiving equipment and stack modules. The central processing unit is deployed in the computer room and connected to each node through a dedicated line. The test transmits data streams from different protocols in real time, extracts features using link quality evaluation and delay analysis, and performs anomaly detection and fault diagnosis combined with dynamic routing algorithms. During the test, three types of anomalies are simulated: protocol switching, data congestion, and link interruption, and verification is carried out under three environments: low load, normal, and high load. The protocol switching delay and throughput are recorded to test the real-time processing capability and accuracy of the system. The environmental noise intensity is set to 40 dB, 50 dB, and 60 dB respectively.

4.2 Protocol Switching Performance Test

The performance test mainly evaluates the response capability and stability of the system in different protocol switching scenarios. In the performance test, the system proposed in this paper is used to simultaneously process data streams from IP and Non-IP protocols, and its performance under different concurrency conditions is evaluated. The data of each data stream is transmitted to the central processing unit in real time through the dual stack, and undergoes processing steps including protocol parsing, routing selection, security encryption, and data forwarding. During the test, indicators such as response time, throughput, and stability of the system are monitored in real time. The performance test results are shown in Table 1.

Table 1. Dual Stack Switching Performance Test Results

Number of Concurrent Signal Sources	Response Time (ms)	Throughput (Frames per Second)	System Stability (Error Rate, %)
10	25	1000	0.05
50	32	980	0.12
100	45	950	0.25
500	48	920	0.35
1000	49.5	900	0.45

It can be seen from Table 1 that when the system proposed in this paper processes high-concurrency data, it can maintain low response time and high throughput, with good stability and low error rate, meeting the design standard of high-concurrency processing. The performance test results verify the excellent performance of the system in high-load and multi-signal source environments, which can ensure the efficiency and reliability of airborne data link communication and meet the requirements of large-scale deployment.

4.3 Data Transmission Performance Test

The performance test mainly evaluates the transmission quality and integrity of the system under different interference environments. In the performance test, different intensities of electromagnetic interference are simulated to evaluate the survivability of the system in complex environments. The data of each data stream is transmitted to the central processing unit in real time through the dual stack, and undergoes processing steps including protocol parsing, routing selection, security encryption, and data forwarding. During the test, indicators such as bit error rate, packet loss rate, and data integrity rate of the system are monitored in real time. The performance test results are shown in Table 2.

Table 2. Data Transmission Performance Test Results

Environment Type	Bit Error Rate (BER, %)	Packet Loss Rate (PLR, %)	Data Integrity Rate (%)
Low Interference	0.001	0.05	99.95
Normal Environment	0.005	0.10	99.90
High Interference	0.010	0.20	99.80

It can be seen from Table 2 that the system proposed in this paper can maintain excellent transmission quality under different interference environments, with low bit error rate and packet loss rate, and high data integrity rate, meeting the design requirements of airborne data link communication. The performance test results verify the system's strong anti-interference ability and stable transmission performance, which can ensure the reliability and integrity of data transmission in complex electromagnetic environments.

5. Conclusion

The system designed in this paper realizes efficient monitoring and accurate transmission of airborne data link signals through the dual stack architecture and multi-module collaborative work, and has good robustness and scalability. The experimental results verify the excellent performance of the system under different environments, providing a reliable solution for the integration and upgrading of avionics systems. In the future, we will further optimize the algorithm to improve the system's adaptability in extreme electromagnetic environments, promote the intelligent development of airborne data link communication technology, ensure the safety of signal transmission, and contribute to the technological progress of the industry.

References

[1] Liu Y, Jin H, Yu Q. Research on transmission waveform structure and rate scaled of new generation data link//Proceeding of 2017 International Conference on in formation Science and Control Engineering. Changsha: IEEE, 2017: 1686-1689.

[2] Qing L. IP communication architecture and over-head performance of heterogeneous tactical wireless network for air platforms. Telecommunication Engineering, 2019, 59(9): 1020-1025.

[3] Yin H. Design of hydroacoustic data communication system based on carrier. Audio Engineering, 2025, 49(4): 67-69.

[4] Wang W, Wang K, Fu X W. Design of visible light communication system based on VCSEL. Information Technology, 2025(7): 1-8.

[5] Liang Z Y, Kuang J R, Dang T, et al. Design of wireless communication system for offshore converter station. Southern energy construction, 2024, 11(4): 88-101.

[6] Chen Y. Design of communication system for aerial relay station UAV. Wireless Internet Science and Technology, 2025, 22(12): 54-57.

[7] Xie H P, Wang H, Guo M. Design and implementation of convergent communication system in refining and chemical enterprise . Modern Information Technology, 2025, 9(14): 15-20.

[8] Zhang G D, Wang X H, Liu X Y, et al. Design and research on WIFI6 wireless communication system under intelligent transformation of coal mine. China High-Tech, 2023(9): 47-49.

[9] Hu Y W. Design and performance evaluation of 5G-based power distribution network automation communication system. China Broadband, 2023, 19(12): 55-57.
[10]Wang H. Design and availability evaluation of next generation train control data communications system based on LTE-M. Urban rapid rail transit, 2023, 36(1): 156-167.

