

Optimization of Latency and Enhancement of Reliability in Air-Ground Data Links under Single-Pilot Operations Mode

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Abstract:

Air-ground data link serves as the critical technological foundation for enabling single-pilot operations. Consequently, optimizing its latency and enhancing reliability are paramount for improving flight safety and operational efficiency. This paper synthesizes recent advancements in optimization techniques for air-ground data links: deep learning-based channel estimation algorithms significantly improve aircraft communication capabilities in complex environments; Aircraft Condition Monitoring System (ACMS) facilitates real-time transmission of flight parameters and ground control instructions; and the Controller-Pilot Data Link Communications (CPDLC) and Automatic Dependent Surveillance-Contract (ADS-C)centric architecture enables continuous state monitoring, thereby reducing operational risks. Reducing latency and improving stability in air-ground data links will profoundly and positively impact civil aviation safety and efficiency, unmanned aerial vehicle logistics, urban air mobility, as well as the development of low-altitude economy and intelligent industries. In the future, with the deep integration of new-generation communication technologies such as 5G-ATG and satellite internet, the performance of air-ground data links will witness a qualitative leap, laying a solid foundation for the full-scale intelligence of air transportation.

Keywords: Channel estimation; Flight status monitoring; Delay optimization; Air-ground data link communication system

1. Introduction

With the advancement of the aviation industry, the single-pilot operation model has emerged as a future

trend due to its advantages of high efficiency and low operational costs. This model simplifies crew configuration, thereby reducing labor expenses, and streamlines cockpit decision-making processes by eliminat-

ing dual-pilot coordination, which enhances operational efficiency. The air-ground communication network, which is composed of low-altitude communication equipment and ground communication equipment, takes advantage of the rapid deployment and high elevation gain of aerial platforms such as UAV. It effectively expands the communication relay range in complex electromagnetic environments [1]. Advanced automation systems further mitigate human operational errors, thereby improving safety. However, the single-pilot operation model imposes higher requirements on the reliability of air-ground data links. The air-ground data link is a communication network that facilitates digital information exchange between aircraft and ground systems via radio, serving as a core infrastructure for modernizing air traffic management and digitizing flight operations by replacing traditional voice communications. The application of air-ground data links enhances safety and efficiency, reduces human errors, optimizes route and airspace capacity, and lowers operational costs. Current research on air-ground data links has made significant progress: deep learning-based channel estimation techniques have improved the accuracy of channel estimation in various operational environments; the Aircraft Condition Monitoring System (ACMS) enables the transmission of critical flight parameters and ground-based commands via air-ground data links, facilitating real-time monitoring of aircraft flight status; and the establishment of an air-ground data link communication system based on Controller-Pilot Data Link Communications (CPDLC) and Automatic Dependent Surveillance-Contract (ADS-C) allows for continuous aircraft state monitoring, thereby reducing accident risks.

Channel estimation algorithms are employed to analyze signal distortion for communication optimization. Traditional methods exhibit poor adaptability in dynamic aviation environments. This study utilizes Convolutional Neural Networks (CNN) to automatically extract channel features, thereby enhancing the estimation accuracy of OFDM systems, significantly reducing bit error rates, and improving the stability of air-ground data links. ACMS collects flight parameters via multiple sensors, processes the data analytically, and facilitates bidirectional air-ground communication and status monitoring through ACARS, thereby supporting real-time decision-making. ADS-C enables real-time transmission of four-dimensional aircraft trajectories via air-ground data links, particularly suitable for radar-blind zones such as oceanic areas. Its on-demand reporting mechanism optimizes communication load and collaborates with CPDLC to support Trajectory-Based Operations (TBO). This study optimizes protocols and compression algorithms to enhance transmission efficiency and reliability. CPDLC improves air

traffic management efficiency through digital text-based instructions and supports 4D-TBO collaborative management. The research further refines the air-ground data link architecture by reducing redundant design and ensuring real-time anti-jamming communication under single-pilot operations.

This paper aims to systematically review the research progress and development trends of key technologies of air-ground data link under the single-pilot flight mode. It focuses on technologies such as channel estimation, ACMS system, ADS-C surveillance and CPDLC communication, and analyzes the technological breakthroughs in intelligent channel estimation based on deep learning, real-time flight status monitoring and analysis, adaptive reporting and compression transmission mechanism, and digital anti-jamming communication system. It also provides prospects for future research directions, offering theoretical references and technical support for enhancing the stability, real-time performance and security of air-ground data link in complex aviation environments.

2. Solutions for Delay Optimization and Reliability Enhancement in Ground Data Link

2.1 Air-Ground Data Link

Air-ground data link refers to a communication link established between aircraft and ground systems through radio data link technology, which is used for two-way and real-time transmission of digital information. It is a communication system for real-time data exchange between humans piloting aircraft or Unmanned Aerial Vehicles (UAVs) and ground terminals. It is also one of the core technologies of air traffic management and UAV control, mainly used for transmitting flight status information, mission instructions, control signals, etc. The basic principle of air-ground data link is to achieve two-way data transmission between aircraft and ground stations through wireless communication technologies such as radio and satellite communication. Sensors on the aircraft, such as radar, electro-optical equipment, and navigation systems, collect flight status data, which is then digitized, encoded, and modulated onto carrier signals, and sent to the ground station via radio frequency or satellite links. The ground terminal decodes and fuses the received signals for analysis and decision-making, and finally sends control instructions to the aircraft, thus forming a closed-loop control. The communication delay of air-ground data link is in the millisecond to second range, which makes the aircraft's decision-making timely. Signal transmission adopts an-

ti-interference technologies such as frequency hopping and spread spectrum to adapt to complex electromagnetic environments. The large bandwidth supports the transmission of multiple types of data, and the communication has confidentiality and security. Currently, the limited focus of airborne real-time processing on preprocessing underutilizes the air-ground data link. Developing integrated onboard capabilities for real-time analysis and telemetry is essential to unlock this link’s potential for bidirectional, real-time interaction, thereby significantly enhancing flight test and development efficiency [2].

2.2 Channel Estimation Technology based on Deep Learning

As shown in Figure 1, this framework mainly consists of an input layer, a hidden layer, an output layer, and network training. The workflow begins with initializing the

channel response using the pilot sequence through the LS algorithm and combining the data sequence to construct the channel sample dataset and perform division. The core of the model adopts a multi-scale convolutional neural network, integrating modulation filters and CNN modules for feature extraction, and enhancing feature robustness through the MaxPooling layer; subsequently, the Bidirectional Long Short-Term Memory Network (BiLSTM) is used to capture the time series dependency, and then processed further through the fully connected DNN layer, ultimately outputting the channel response sequence $h(0)$ to $h(8)$. Network training employs the ADAM optimizer, continuously optimizing model parameters by calculating the loss between the predicted output and the theoretical output, thereby improving the estimation accuracy and adaptability in the air-ground channel environment.

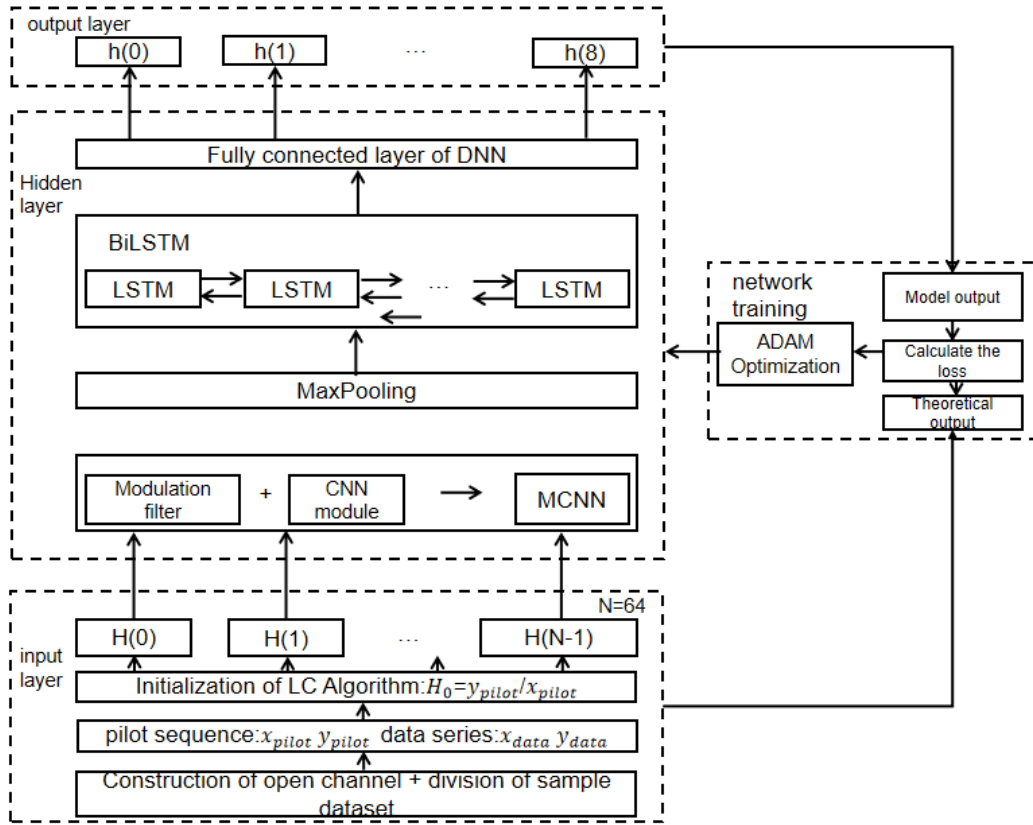


Fig. 1 Channel Estimation Framework Based on Deep Learning

2.2.1 Network input layer

TDL model with intermittent multipath components:

$$h_{2-ray,F}^{(e)}(\tau, p) = \alpha_{0,p} e^{-\frac{j2\pi R_{l,p}}{\lambda} \delta(\tau - \tau_{0,p})} + \alpha_{s,p} e^{-\frac{j2\pi R_{l,p}}{\lambda} \delta(\tau - \tau_{s,p})} \quad (1)$$

The literature mentions that the TDL model of the open-air channel has up to 9 taps at most. Therefore, the expression of the channel impulse response of the TDL model

The impulse response of the two-path open space channel at time p is:

adopted in this paper is as follows:

$$h_{9-ray}(n) \approx e^{-j\theta_1} \delta(n) + \alpha_{s,n,p} \Gamma_{p,F} D_p r_F e^{-j\theta_2} \delta(n-1) + \sum_{a=3}^9 \alpha_a z_a e^{-j\theta_k} \delta(n-a) \quad (2)$$

In the formula: α and θ represent the amplitude and phase respectively, $z \in (0, 1)$ is used to describe the probability of the tap switch; the subscript a indicates the a -th intermittent multipath component, where a is an integer ranging from 3 to 9.

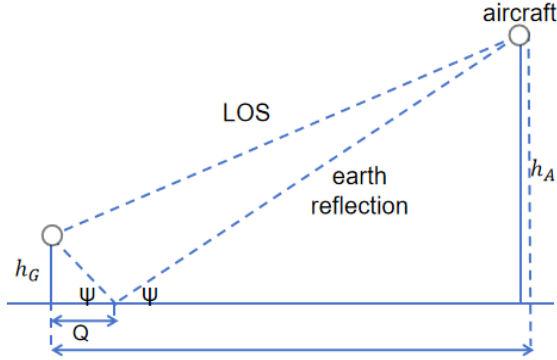


Fig. 2 Dual-Path Open Space Channel Model

In Figure 2, h_A and h_G represent the distances from the ground to the aircraft and the ground antenna respectively, d is the ground distance between the two, and ψ is the grazing angle of the ground reflection component. This model assumes that the ground reflection characteristics are mainly influenced by two factors: one is the flatness of the ground, and the other is the vegetation coverage within a radius Q around the ground station. Specifically, the effective ground reflection point must be located within a circular area with the ground station as the center and a radius of Q , and the following equation exists:

$$Q = \frac{dh_G}{h_A + h_G} \quad (3)$$

In the channel estimation process, first, the air-ground channel model is constructed based on the TDL model established in Figure 1, and the corresponding channel coefficient data set is generated. Then, the data set is divided into pilot and data parts. The pilot sequence is processed using the least squares (LS) estimation algorithm to estimate the channel state information (CSI) at the pilot positions. The specific calculation expression is:

$$H_{LS}(q) = \frac{(q)y_{pilot}}{(q)x_{pilot}} \quad (4)$$

Here, $H_{LS}(q)$ represents the channel response of the q th subcarrier obtained through LS estimation, and $x_{pilot}(q)$ and $y_{pilot}(q)$ correspond to the pilot signals transmitted and received on the q th subcarrier, respectively. For the CSI of the data symbol part, the initial value is set to zero. Therefore, the input data of the neural network can be expressed as:

$$H = [H(0), \dots, H(n), \dots, H(N-1)] \quad (5)$$

Here, $H(n)$ represents the channel state information at the n th OFDM symbol. It should be noted that since the channel data is in complex form, before inputting it into the neural network, the real and imaginary parts of the data need to be separated and combined into a new dimension as the network input [3].

2.2.2 Hidden layer of the network

CNN first utilize convolution operations to extract local features from continuous word sequences, and then filter out key information through pooling operations [4]. Traditional convolutional neural networks often contain a large number of redundant parameters due to their multi-level convolutional structure, resulting in high computational complexity. The inherent correlation and dependency among the parameters in CNNs can also affect the performance of the model. To optimize this issue, an improved one-dimensional CNN architecture - Modulated CNN (MCNN) - is proposed [3]. MCNN configures multiple convolution kernels of different sizes to construct parallel convolution channels, thereby being able to extract diverse and complementary feature patterns from the same input to capture richer feature representations [4]. The core idea is to integrate modulated filter technology into the network design, thereby significantly reducing the number of parameters while maintaining the feature extraction capability.

The design of modulated generation convolution kernels has the following significant advantages: Firstly, the modulated filter can effectively optimize the characteristics of randomly initialized convolution kernels and enhance the feature extraction efficiency of the network through directional guidance. Secondly, this technology adopts a modulated filter sharing mechanism, which significantly reduces the number of parameters in deep neural networks and thus achieves a lightweight model design. Based on these advantages, this paper constructs a new channel estimation network combining MCNN and BiLSTM. The core of the Long Short-Term Memory (LSTM) network lies in using hidden states to preserve the information that has passed through its input, but it can only retain past information. In some cases, predictions need to be jointly determined by several previous and subsequent inputs, which makes the prediction results more accurate. Therefore, BiLSTM model was proposed based on LSTM, which solves the vanishing gradient problem caused by Recurrent Neural Networks(RNN) [5].

2.2.3 Network output layer

The output layer of the network is responsible for generating the final channel coefficient estimates, and its output includes the real and imaginary components of the channel response. During the hidden layer processing stage of the system, the output of the BiLSTM network is subjected to feature integration and dimension transformation through a fully connected layer, and the real and imaginary part information is fused into the final output by means of weighted summation [3].

2.3 Flight Status Monitoring and Data Processing Based On Air-Ground Data Link

2.3.1 ACMS system

As shown in Figure 3, the core function of the ACMS system is to apply on-board equipment to collect flight critical parameters in real time, such as Mach number, fuel flow and engine temperature, etc.(ACMS messages are transmitted through the ACMS system, ACARS system, VHF or satellite communication system, ground

data receiving system, ground data processing system and engine monitoring system to complete the entire process from message to engine monitoring. ACMS message data is generated by various sensors and monitoring on-board equipment installed on the aircraft for monitoring and collecting flight parameters and the status of aircraft systems.). By processing these data, the operational status of the aircraft can be determined in a timely manner, thereby providing reliable data support for subsequent maintenance work. The workflow mainly includes: first, collecting parameter data from various monitoring points through multiple sensors; then analyzing and processing the obtained data, and triggering corresponding processing mechanisms based on the analysis results; and then using the ACARS system to send relevant information to the ground end, where ground professionals conduct in-depth analysis, and the analysis results are sent back to the onboard system, thus achieving two-way communication between the air and the ground. All data can be presented intuitively on the terminal display, facilitating real-time monitoring and analysis.

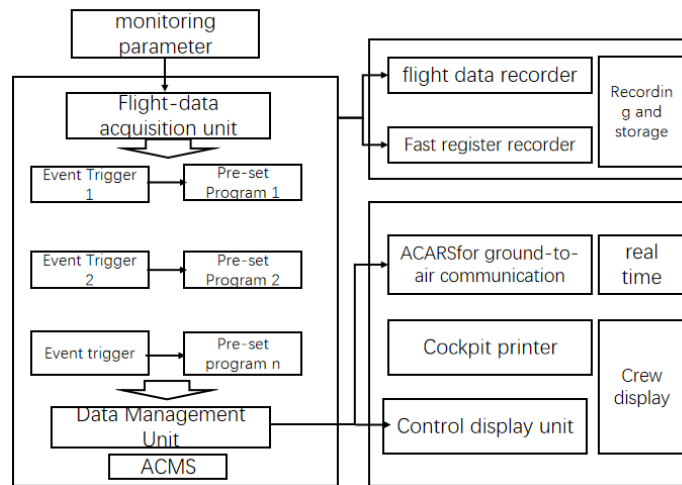


Fig. 3 Overall Framework of the ACMS Monitoring System

2.3.2 VHF air-ground data link communication

Real-time monitoring of aircraft status requires two conditions: one is to ensure stable communication between the ground and the airborne platform, and the other is to rely on the background system for in-depth analysis and mining of data. To ensure the operation of the ACMS system, the first problem to be solved is to achieve communication between the aircraft and the ground. Practice has shown that the VHF air-ground data link has greater advantages in achieving rapid reporting and receiving and transmitting fault-related information. The specific communication process is shown in Figure 4.

As can be seen from Figure 4, for the ACMS air-ground

data link system to exchange information with the company's gateway, it needs to go through the ACARS data link system. Data encapsulation and transmission are achieved through the ARINC618/ARINC620 protocol. Then, by embedding the ActiveX control Socket.ocx and using the message communication server, the process is realized. After receiving the information, the ground processing system will parse the report [6].

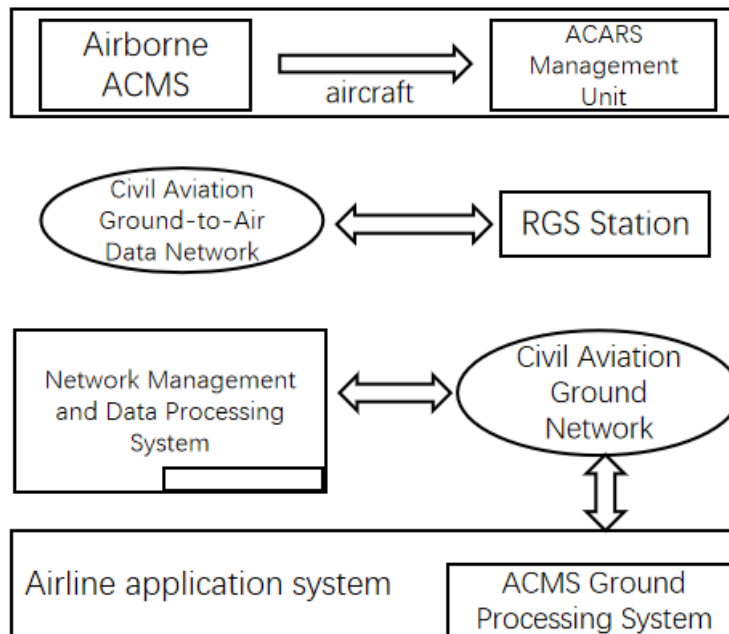


Fig. 4 VHF Air-Ground Data Link Communication Process

2.4 Build An Air-Ground Data Link Communication System Based On CPDLC Communication And ADS-C Surveillance

Building an air-ground data link communication system centered on CPDLC and ADS-C can significantly enhance the efficiency of air traffic management. CPDLC converts traditional voice instructions into precise digital text instructions, ensuring unambiguous transmission and confirmation of instructions; while ADS-C automatically reports the four-dimensional position and status information of the aircraft at agreed intervals, providing continuous and accurate aircraft trajectory monitoring for the control side, which is conducive to the high-precision prediction and refined management of aircraft trajectories in the future.

2.4.1 CPDLC communication

CPDLC based on the Aeronautical Telecommunication Network (ATN) in the airway environment is expected to achieve performance improvements over the current voice communication. Although voice communication will remain as a backup means for non-routine or emergency situations in the future, CPDLC is expected to gradually become the dominant communication method. This system will first digitally replicate the current communication mode and then evolve in conjunction with the Air Traffic Management (ATM) system towards a trajectory-based operation mode, providing corresponding functional support. It is expected that the implementation of CPDLC will help alleviate communication congestion in the voice

frequency band, reduce the workload of flight crews and air traffic controllers, and decrease the probability of crew operational errors [7].

Functions of CPDLC: CPDLC is a new type of data link system and the most widely used application of data link technology in modern air traffic control. As an air traffic control communication means that uses data instead of voice between controllers and pilots, CPDLC enables direct flight data exchange between controllers and pilots during flight operations and significantly reduces the risk of accidents caused by misunderstandings or information errors due to voice communication [8]. CPDLC clearances are displayed as electronic messages on a dedicated screen in the aircraft, while CPDLC requests are integrated directly into the air traffic controller's radar display. The transmission of messages via CPDLC typically requires approximately 20 seconds. Voice communication is generally no longer employed for the types of interactions described above[9].

The communication process of CPDLC: after the crew members complete the initialization login (LOG ON) step for the Air Traffic Services Facilities Notification (AFN), the Flight Management System (FMS) will send an "AFN CONTACT" message to a designated ATSU, informing it of the acceptable air traffic services capabilities. The ATSU will reply with "AFN ACKNOWLEDGEMENT", and the AFN login will be completed.

CPDLC connection establishment: The ground control unit acts as the initiator of CPDLC. After receiving the

“CONNECTION REQUEST” message from the ATSU, the aircraft will automatically reply with “CONNECTION CONFIRM”, thereby establishing an effective CPDLC connection.

Establishing AFN login association with the next control unit (NDA): First, when the current control unit CDA needs to send a message to notify NDA, it will send an “AFN CONTACT ADVISORY” message to the aircraft to inform it to log in to AFN with NDA. After receiving the message, the aircraft will reply with an “AFN RESPONSE” message and send an “AFN CONTACT” message to NDA to request AFN login. Upon receiving the message, NDA will reply with “AFN ACKNOWLEDGEMENT”, and the aircraft will also reply to CDA with “AFN COMPLETE” to indicate that it has established an AFN login association with NDA.

CPDLC connection termination: The ground control unit CDA will send an “END SERVICE” message to the aircraft at the appropriate time and location to initialize the termination of the CPDLC connection. Subsequently, the aircraft will reply with a “DISCONNECT” message to terminate the CPDLC connection. In special circumstances, the aircraft can also proactively send a “DISCONNECTION REQUEST” message to forcibly terminate the connection.

2.4.2 ADS-C Technology

Functions of ADS-C: unlike CPDLC, which is mainly used for communication between pilots and controllers, ADS-C is a new surveillance technology. As a contractual automatic dependent surveillance system, it operates between aircraft providing ADS information and ground stations receiving ADS reports based on agreements and corresponding relationships. The system transmits the aircraft’s position, speed, and other status parameters calculated by on-board equipment to the ground station via the air-ground data link, and then the ground network transmits the data to the surveillance center. The surveillance center generates continuous tracks by processing each received data point, thereby achieving real-time monitoring of the aircraft’s operational status [8].

Data link services, such as the Automatic Dependent Surveillance - Contract (ADS-C) as defined by the International Civil Aviation Organization (ICAO), enhance aircraft situational awareness and effectively support air traffic safety, airspace capacity improvement, and environmental protection [9]. As a core component of modern aviation infrastructure, ADS-C can automatically report key information such as aircraft position, altitude, and speed upon request from ground systems for surveillance and flight path compliance monitoring. Standard reports include contract type and route parameters, and aircraft

can also send emergency information when necessary [10]. Contract Types of ADS-C: the initiation of ADS-C contracts is the responsibility of the Air Traffic Services Unit (ATSU). The ATSU can establish multiple contracts for the same aircraft, and each contract requires the collection and transmission of a series of basic information. If the ground needs to obtain additional data, it should be clearly specified in the contract. The specific type of contract depends on the type of information required and the special conditions that trigger the sending of ADS-C reports. The specific classification is as follows:

Periodic Contract: The aircraft sends ADS-C messages at specific time intervals as required by the ATSU. The ATSU selects the data groups included in the periodic contract and can adjust the reporting period and update frequency at any time.

Request Contract: If the ATSU does not receive the contract data from the aircraft within the specified time, it can initiate a request contract to request the aircraft to transmit a single ADS-C report. Periodic contracts cannot be modified or terminated while other ADS-C contracts are in progress.

Event Contract: When the aircraft system detects that the preset status conditions by the ATSU, such as route point changes, lateral deviations, or vertical rate changes, are met, it automatically sends a report to the ATSU. The event contract remains valid until the ATSU actively terminates it or the triggering event occurs.

AFN Login and ADS-C Connection Process: the primary prerequisite for using the data link ADS-C is AFN. Users need to send a login request to the ground station. Upon receiving the request, the ground system will send a request for an ADS-C contract to the aircraft. When the ADS-C function is activated, the aircraft will automatically connect, thereby transmitting information such as its position, altitude, and speed to the ground station [8].

3. Summary

This paper focuses on the research of air-ground data link under the single-pilot operation mode, aiming to enhance the reliability, real-time performance and security of the air-ground data link in complex aviation environments. The research focuses on key technologies such as channel estimation, ACMS system, ADS-C system and CPDLC communication, providing effective theoretical and technical support for the development of future civil aviation air-ground integrated communication systems.

This paper first introduces the concept and application of air-ground data link, explains the communication process of air-ground data link, and then reviews and summarizes the existing air-ground data link technologies. To im-

prove the signal processing accuracy of air-ground data link, deep learning-based channel estimation technology is adopted; in the aspect of multi-sensor data fusion, the ACMS system is applied to achieve real-time supervision of important flight parameters and real-time air-ground decision-making; and a communication system of air-ground data link based on CPDLC communication and ADS-C surveillance is proposed to achieve protocol optimization and anti-interference communication.

The optimization of air-ground data link has significant impacts on the military, civil aviation and commercial fields. In the military field, it enables real-time information sharing and joint all-domain operations. In the civil aviation field, it provides data support for dense flight traffic management, real-time aircraft health monitoring and predictive maintenance, significantly enhancing flight safety and efficiency, and improving passenger network experience. In the commercial field, it supports applications such as unmanned aerial vehicle logistics, precision agriculture and large-scale automated inspection, giving rise to an aerospace economic model and serving as a key infrastructure for intelligent upgrades in various fields. Predictive maintenance based on real-time data will greatly reduce mechanical hazards and ultimately build an efficient, safe and green next-generation aviation transportation system.

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