

A Data-Centric Approach of Network based Aeronautical Mobile Telemetry System Architecture Design

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Abstract :

In this paper, we provide a Data-Centric approach of designing a network based aeronautical mobile telemetry system inspired by the well known OMG open standard, *Data Distribution Service*, which fully utilizing the real time performance of RTPS layer transmitting abilities and sophisticated designed QoS rules binding to pre-defined specific data types, data writers and readers. Two general data buses, Data Databus (DDB) and Operation and Control Databus (OCDB) are proposed alone with the concept of Flight Test Radio Access Network, which give the flight test organizer a flexible and resiliency system architecture to perform completed multiple test articles and multiple ground facilities flight test missions.

Key words: Data-Centric, Aeronautical Flight Test, Radio Access Network.

1. Introduction

In the development process of civil aircraft, flight testing is an indispensable and critical phase, spanning from research and design, airworthiness certification, to batch production validation and design optimization. It is essential to establish an Air-to-Ground communication link to transmit test data and real-time video to the ground monitoring and command center during the flight. This provides reliable real-time monitoring information for flight test commanders and ground engineering personnel, ensuring flight test safety and improving test efficiency. With the advancement of Air-to-Ground communication technology, the transmission mechanism has evolved from serial unidirectional to bidirectional networking. Based on Air-to-Ground networking and test systems, this paper proposes a data-centric Air-to-Ground networked telemetry communication system utilizing Data Distribution Service (DDS). Leveraging DDS's technical advantages—high real-time performance, high reliability, loose coupling, and orchestration capability—a robust and engineerable architecture is constructed. This system is compatible with current equipment capabilities while also adapting to the future evolution of integrated air-space-ground complex networking.

The remainder of this paper is organized as follows. Section 2 briefly introduces the requirements analysis for flight test telemetry and traditional telemetry communication systems. Section 3 presents the fundamentals

and capabilities of Data Distribution Service (DDS) technology. Section 4 proposes the data-centric Air-to-Ground networked telemetry communication system architecture, including its functional components and key system capabilities and finally, section 5 concludes the paper.

2. Requirements Analysis and Traditional Approaches

2.1 Requirements

In flight testing, the measurement system must be equipped with a data acquisition system onboard the test aircraft in accordance with the test mission and measurement outline. During flight tests, this system is responsible for data acquisition, real-time monitoring, and recording from diverse data sources, including aircraft buses, installed sensors, onboard video, and specialized test systems.

On the airborne side, flight test and instrumentation engineers control and monitor the test system in real time. On the ground side, flight test command personnel and aircraft design specialists can monitor telemetry parameters and video in real time via the telemetry downlink throughout the test mission. This enables them to command and supervise the test process, verify the execution of test points, and promptly identify potential risks.

The airborne measurement system must perform synchronized acquisition and recording of multiple data types based on precise global time synchronization. Test parameters may have

varying sampling rate requirements, and the system must ensure complete and reliable data recording to meet flight test objectives.

For the Air-to-Ground telemetry transmission and ground-based real-time data processing system, it is essential to track the test aircraft in real time during flight, receive and demodulate telemetry data, perform real-time data processing and engineering unit conversion on the ground, and distribute the results to monitoring displays across different aircraft engineering disciplines. This supports ground-based command personnel in successfully executing flight test missions.

2.2 Traditional SST

2.2.1 Normal SST and Chapter 7

The IRIG-106 standard[1] defines the traditional serial communication-based telemetry transmission system, which employs Pulse Code Modulation (PCM) to carry data. There is a standard rectangular frame structure, where each major frame is divided into M minor frames (subframes). Each minor frame consists of a synchronization word, a subframe ID, and N parameter words containing the actual payload data. The airborne telemetry system performs continuous phase frequency modulation and transmission of this data.

With the advancement of flight test measurement system technologies, ethernet-based airborne measurement systems have gained widespread adoption. The new generation of FTI system supports various standardized Ethernet based formats such as IENA, IRIG-106 Chapter 10, as well as proprietary network packet formats from different data acquisition Equipment manufacturers, enabling networked data acquisition, transmission, and recording. To maintain compatibility with legacy serial telemetry transmission equipment and communication protocols, the standardization organization RCC TG introduced a packet telemetry downlink standard in 2017, defined in IRIG-106 Chapter 7. This chapter involves a fundamental principle of encapsulating network packets into the IRIG-106 Chapter 4 serial data stream as defined in the previous section. On the ground station side, an IRIG-106 Chapter 7 gateway extracts and reconstructs the original network packets from the synchronized bitstream after frame synchronization. These packets are then processed and monitored within the ground data processing subsystem.

2.3 A glance at TmNS

Advancing further into network technology applications, the IRIG-106 Network Telemetry

(TmNS) standard was developed through years of discussion, as defined in Chapters 20 to 28 of the standard. The overall architecture is illustrated in the figure below.

The standard establishes a parallel architecture between networked telemetry transmission systems and traditional serial PCM telemetry. A bidirectional TmNS radio frequency (RF) link is established between airborne and ground systems to transmit TmNS-formatted messages, enabling networked interoperability between Air-to-Ground test systems. Test aircraft, ground station systems, mission control, and ground support equipment all synchronize time via direct GPS timing or IEEE 1588-compliant switches, facilitating networked transmission of mission configuration data, device control information, telemetry monitoring data, and other critical information.

The TmNS system specifies the use of SOQPSK-TG modulation for Air-to-Ground data communication. By leveraging appropriate RF bands and bandwidth configurations, it supports uplink transmission and establishes a bidirectional RF communication link between ground-based auto-tracking antennas and airborne TmNS gateways, typically employing Time Division Multiple Address (TDMA) with separate uplink and downlink time epoch. This system can reuse existing telemetry ground station RF infrastructure while achieving single-station coverage within a 300 km radius.

3.Data-Centric Real Time Communication

3.1 Standardization and Typical applications

This paper introduces Data Distribution Service (DDS) [2] to construct a data-centric Air-to-Ground networked telemetry communication system as the middleware for flight test wireless access. DDS is an open standard protocol defined and maintained by the Object Management Group (OMG), initially released in 2004. It's designed to enable reliable, high-performance, interoperable, real-time, and scalable data exchange using a publish-subscribe mechanism.

Data Distribution Service originated from early U.S. Navy shipboard applications, where it was developed to provide a universal communication middleware for integrating heterogeneous devices and subsystems from diverse vendors across complex warship systems[3]. In the field of intelligent driving, DDS has been selected by the Automotive Open System Architecture (AUTOSAR) as the standard in-vehicle communication middleware system[4]. With the rapid advancement of smart vehicles and autonomous driving technologies, DDS has been successfully deployed in commercial

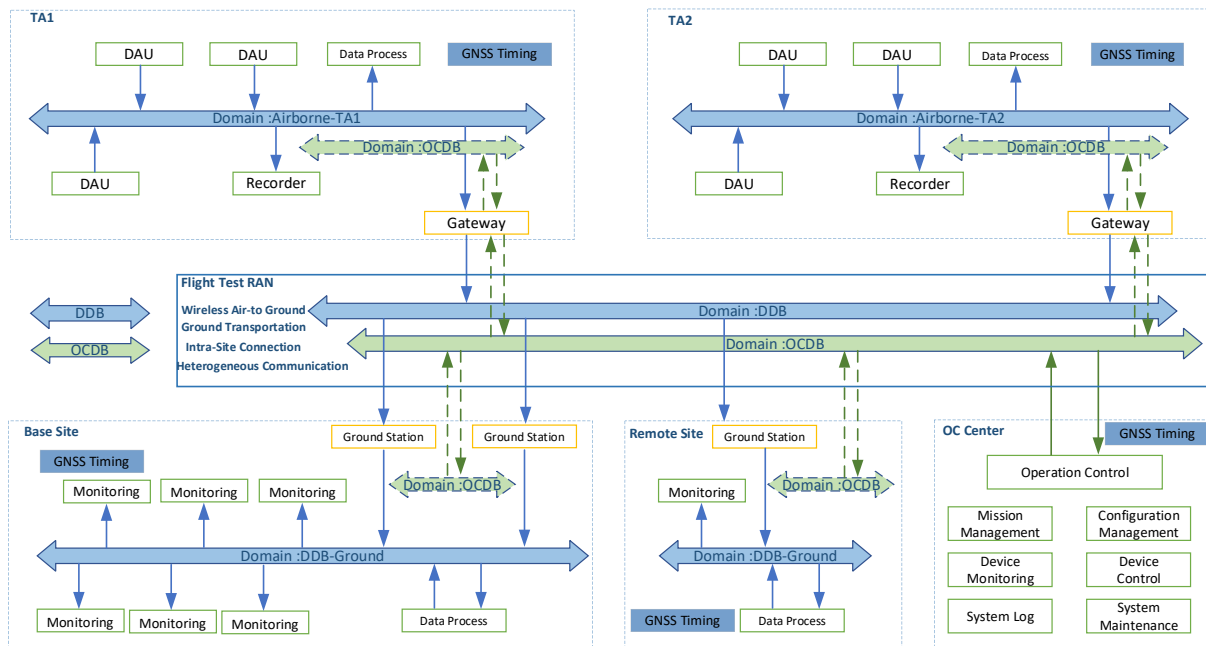


Fig. 1. Data-Centric Architecture for Radio Access Networks in Flight Test Applications.

projects, such as XPeng Motors, enabling inter-domain communication in modern intelligent vehicles. Data Distribution Service was adopted as the standard communication middleware by the Robot Operating System 2 (ROS 2)[6], designed to establish a standardized development, simulation, verification, and deployment software platform for production-ready robotic control, communication, and multi-robot collaboration.

Multiple complex real-time communication systems across various industries have integrated Data Distribution Service technology. For example, the ATLANTIDA consortium employed DDS in the design of an air traffic management system involving 34 distinct organizations for civil, military, and unmanned aerial vehicle (UAV) operations.

3.2 Technical features

DDS is characterized by the following key technical features, which enable its adaptable application across various real-time data exchange scenarios.

- Data-Centric Communication Middleware,
- Dynamic Discovery,
- Multiple QoS Rules,
- Dynamic Adjustment based on Meta Data File,
- Multiple security layers.

4. Proposed system architecture

4.1 General architecture

The data-centric Air-to-Ground networking architecture requires the communication system's foundational framework to follow a $1+M+N$ paradigm, comprising one primary base station, M secondary base stations, and N specialized test field sites—collectively forming a unified wireless access network for flight testing. The schematic diagram of this overarching architectural design is presented in Figure 1.

Physical link perspective:

The proposed architecture establishes bidirectional wireless RF communication links between airborne and ground systems to ensure reliable data transmission between test aircraft and ground stations.

For cross range connectivity between different geographical sites, dedicated leased lines or private transmission solutions are employed, with IP transport and cybersecurity measures ensuring secure multi-site networking.

All test aircraft achieve time synchronization through GNSS equipment, establishing a unified time reference. Each ground facility incorporates a GNSS-based timing distribution subsystem to disseminate synchronized clock signals, enabling high-precision time synchronization among ground stations, mission control, data processing systems, and airborne systems. The Air-to-Ground wireless links may adopt TDD scheme to maintain synchronous communication between test aircraft and ground stations.

Logical architecture perspective:

Based on the data-centric design philosophy, the Flight Test RAN carries two distinct service buses:

Data Databus (DDB):

Responsible for transmitting critical flight test operational data including real-time acquired test parameters (for acquisition, transmission, processing, and monitoring) and airborne video streams and other sensor data collected by test aircraft. These constitute the mission-critical payload during flight tests.

Operation and Control Databus (OCDB):

Handles centralized transmission and control of Flight test mission management, Participant equipment monitoring, Software/hardware version information and control, Equipment maintenance operations and Remote diagnostics and control commands. Adopting an in-band telemetry mechanism analogous to satellite TT&C systems, where management and control data are transmitted alongside the payload feed with different type of QoS rules to make sure the real time performance of Data information and the reliability of control commands.

4.2 System Key Components**Airborne Systems**

An onboard test system is installed in each test flight aircraft, featuring a networked architecture. The system accesses the Flight Test RAN wirelessly through an airborne gateway, establishing air-to-ground network communication.

Data acquisition and transmission within the aircraft are managed through publishing and subscribing within the corresponding data bus Domain, enabling a highly integrated and tightly coupled onboard test system. The airborne gateway, serving as an edge device, subscribes to data requiring telemetry transmission and monitoring within the aircraft's data bus Domain and publishes this data to the Flight Test RAN data bus, facilitating the transmission of telemetry data between air and ground. Diagnostic data, real-time status, configuration updates, RPC communications, and other operational management information are exchanged within the management bus of the onboard test system and published/subscribed to the Flight Test RAN management bus via the airborne gateway.

Ground Systems**a) *Ground Telemetry Station***

The primary equipment at the ground station consists of the ground segment subsystem of the Flight Test RAN. It employs a high-gain, high-dynamic-range self-tracking antenna feed subsystem or a phased array antenna system to establish beam pointing toward the test aircraft. This enables bidirectional Air-to-Ground wireless

communication links with the airborne gateway, facilitating networked data transmission between the air and ground segments.

The ground station serves as the terrestrial endpoint of the Flight Test RAN. Multiple ground stations are interconnected to form the complete Flight Test RAN.

b) *Ground Real-Time Data Processing System*

The ground real-time data processing system performs real-time data processing and engineering unit conversion on telemetry data received from the airborne gateway. It publishes engineering data and onboard video within the real-time data monitoring subsystem of the associated base. Multiple monitoring terminals subscribe to this data for real-time monitoring. Additionally, specific terminals under appropriate network security mechanisms can publish data to the airborne data bus network, enabling bidirectional data interaction and multimedia function like VoIP or Realtime Video chat.

c) *High-Precision Time Synchronization System*

The ground station is equipped with high precision time synchronization devices, which acquire time information from the GNSS subsystem and distribute it within the ground station using protocols such as IEEE 1588v2, IRIG-B, or 1PPS+TOD, ensuring precise time synchronization among all ground-based equipment.

d) *Operation and Control System*

The operation and control system connects to the Flight Test RAN and establishes reliable network connections via an OCDB with equipment and subsystems across ground systems and the onboard test systems of TAs. It subscribes to system management information such as device status and operational logs, enabling unified management of flight test missions. The system centrally controls software and hardware versions of the test systems, achieving integrated operation and control of the flight test infrastructure.

Existing test sites and equipment can be integrated into the operation and management system by adding operation and control terminals. Alternatively, by defining standardized flight test operation and control interface specifications, future ground systems, and even native onboard systems can inherently support operation and control links, forming a standardized solution.

4.3 Payload QoS Mapping**4.3.1 Application to Middleware Mapping**

Tab. 1: Typical DDS QoS Mapping

Databus	Data Type	DDS QoS Mapping
DDB	Realtime Telemetry Data	● <i>BEST_EFFORT</i> for real time monitoring ● <i>TransportPriorityQoS</i> for flow control and forwarding priority ● <i>TIME_BASED_FILTER</i> for downsampling of high-frequency data ● <i>DestinationOrder</i> set to be source timestamp as they captured ● <i>DeadlineQoS</i> for monitoring any abnormal jitter
	Realtime Telemetry Video	● <i>BEST_EFFORT</i> for real time monitoring ● <i>TransportPriorityQoS</i> for flow control and forwarding priority ● <i>DeadlineQoS</i> for monitoring any abnormal jitter
	Data Retrieval	● <i>ReliableQoS</i> for data retrieval ● <i>TransportPriorityQoS</i> for flow control and forwarding priority ● <i>HISTORY_KIND</i> for specific history data depth ● <i>DestinationOrder</i> set to be source timestamp as they captured
ODCB	Device Monitoring	● <i>ReliableQoS</i> for data retrieval ● <i>TransportPriorityQoS</i> for flow control and forwarding priority ● <i>HISTORY_KIND</i> for specific history data depth ● <i>DestinationOrder</i> set to be source timestamp as they captured
	Device Remote Control	● <i>BEST_EFFORT</i> for real time control ● <i>ReliableQoS</i> for control command ● <i>DeadlineQoS</i> for monitoring any abnormal jitter ● <i>OwnershipQoS</i> for authority management
	Configuration Files	● <i>ReliableQoS</i> for file data transmission ● <i>TransportPriorityQoS</i> for flow control and forwarding priority
	Log and Alarm Info	● <i>ReliableQoS</i> for file data transmission ● <i>TransportPriorityQoS</i> for flow control and forwarding priority

As introduced in Chapter 3, the Data Distribution Service (DDS) supports diverse QoS policies, enabling differentiated scheduling of multiple types of data over the same transport layer. Table 1 provides recommended middleware QoS policy configurations for the types of services typically carried by the data bus and the operation and control bus under general conditions.

4.3.2 Middleware to Lower Layer

The system design defines QoS requirements for typical data types and ensures these requirements are matched by the underlying devices carrying the data. For instance, during the Air-to-Ground wireless transmission phase, the priority information from the *TransportPriorityQoS* is mapped to the corresponding QoS identifiers in the transmission layer scheduling strategy between the airborne gateway and the ground station. This enables transmission equipment to handle traffic according to the applied QoS policies.

a) Bandwidth and Flow Control

Under bandwidth-constrained conditions, such as air-to-ground wireless channels, flow control strategies become essential in best-effort network environments. Middleware flow control mechanisms can prevent specific types of data from abruptly consuming all available bandwidth.

b) Forwarding Priority

At the data bus level, different types of service data Topics are assigned priority levels. Predefined policies are applied to the network interface information bound to each Topic. At the network layer, IP packets are marked with DSCP values to identify higher-priority packets in Air-to-Ground and terrestrial transmission networks. These packets are then prioritized during transmission, routing, and switching.

c) Time-Sensitive Communication

For transmitting periodic real-time monitoring data between air and ground, Time-Sensitive Networking (TSN) mechanisms can be introduced. For instance, the periodic gating mechanism defined in IEEE 802.1Qbv can reserve dedicated time slots for critical periodic data, ensuring its reliable transmission. The Object Management Group is currently standardizing DDS extensions for TSN environments. In brief, latency-sensitive QoS policies such as *DeadlineQoS* and *LatencyBudgetQoS* at the DDS layer can be directly mapped to YAML configuration files compliant with IEEE 802.1Qcc.

4.4 Station Management, Operation and Maintenance

The operation and control system achieves unified and integrated operational management of multiple ground stations and the onboard test

systems of flight test aircraft. It serves as a centralized software and hardware platform that utilizes the operation and control bus to establish logical dedicated data transmission channels between various devices. These channels support system operation and management functions such as device monitoring, device control, configuration distribution, and task management.

The introduction of the operation and control system enables the evolution of flight test ground systems from isolated single-station local operations to interconnected multi-station unified management. Based on the Data Distribution Service, it reliably interconnects multiple infrastructures, including fixed ground stations and mobile stations. Leveraging the wireless links established during ground integration tests and flight tests, the operation and control system also interconnects and manages onboard test systems, globally overseeing test missions, software and hardware versions of the test systems, and interfaces with the flight test data platform. This forms a comprehensive integrated solution for ground-based measurement, operation, and control. The functional architecture of the system is illustrated in the figure below.

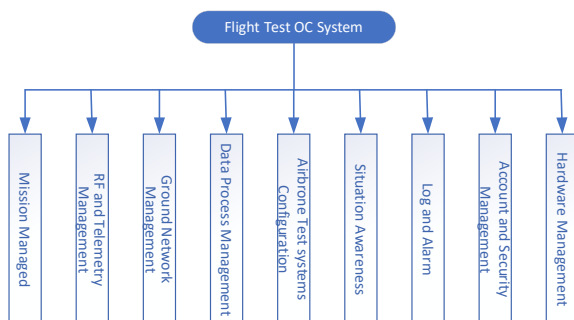


Fig. 2. The functional structure of Flight Test OC System.

4.5 Key Characteristics

4.5.1 TA Dynamic Discovery

In multi-ground station application scenarios for flight tests, remote mobile stations may frequently go online or offline. Leveraging the dynamic discovery mechanism of the Data Distribution Service, which involves mutual discovery prior to data communication, enables flexible and seamless integration and withdrawal of geographically dispersed stations. The operation and management system can promptly monitor the online/offline status of these devices. From the control center, real-time status monitoring and remote control of connected devices can be performed, establishing a comprehensive system-level operation and management framework.

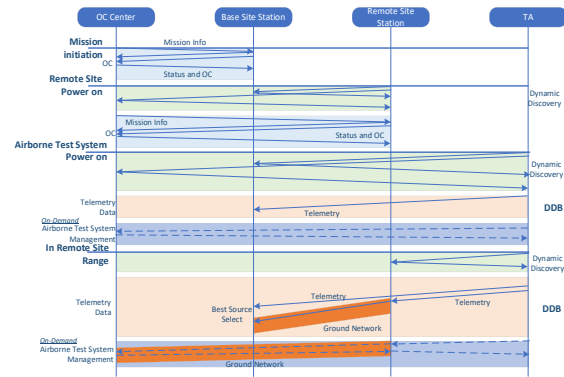


Fig. 3. TA Dynamic discovery based on DDS discovery mechanism.

4.5.2 Best Source Select based on Signal Quality Embedded within Topic

During flight test missions, scenarios involving large airspace spans and long distances at low altitudes are common. As a result, multiple ground stations may be employed to support a single aircraft, enabling continuous telemetry data reception throughout the flight via remote ground stations to ensure data continuity during the test mission. In the scenario of geographically separated ground stations, bitstream-level fusion with ultra-high bandwidth would significantly increase transmission costs. Moreover, the primary objective of remote stations is typically to cover blind zones and extend the airspace coverage. Leveraging the flexibility of DDS's Interface Definition Language (IDL) to define message formats, parameters of different data structures are serialized into bitstreams for transmission. Thus, the telemetry data Topic can include a message quality field, allowing ground stations to encapsulate statistical information, such as estimated SNR, likelihood metrics from soft-demodulation, and LDPC decoding quality indicators, that reflects the demodulation performance at that station and time. This approach mirrors the principle of IRIG DQE strategy, which inserts data quality information into serial data streams. Similarly, DDS enables the embedding of custom quality information within each published Topic. Through efficient Common Data Representation (CDR) serialization, this quality data is transmitted over the network. Upon deserialization, subscribers can extract the quality information, enabling Topic-level message optimization and multi-station fusion at the network packet level, thereby establishing robust multi-station diversity.

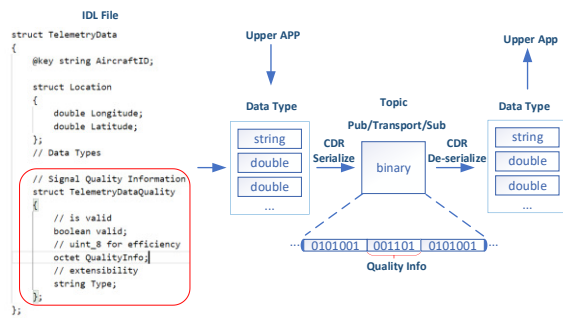


Fig. 4. Define Telemetry Quality Information in IDL file.

The figure below illustrates the specific principle of data fusion and optimization based on Topic-embedded telemetry quality information.

Real-time telemetry data transmitted over networks can not only leverage the built-in QoS policies of the Data Distribution Service to achieve local caching, detect transmission link latency, and identify anomalies such as latency jitter, but also incorporate data quality information directly within the transmitted data. This enables data processing systems to access and evaluate data quality metrics during analysis.

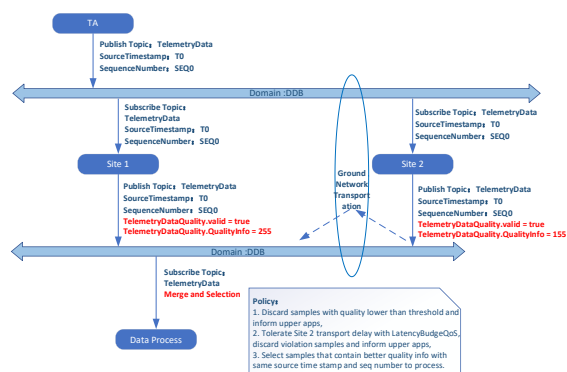


Fig. 5. Best Source Select based on Signal Quality Embedded within Topic.

4.5.3 QoS-Aware Dynamic Content Publishing

The PartitionQoS in DDS is highly effective in handling dynamically changing wireless communication link environments. Its primary principle involves dividing the data to be published into multiple tiers of sub-streams, each containing different levels of information. Taking an SVC-encoded video stream as an example[7], the low-bitrate sub-stream contains only video key frames (I-frames) and some P-frames, while higher-information-rate sub-streams incorporate additional P-frames. During ground-based real-time monitoring, through mechanisms such as the Deadline QoS policy or by utilizing demodulation quality feedback from the information flow described in the previous chapter, the system can perceive the link conditions in real time and subscribe to the appropriate substream

as needed. This ensures both the display quality and continuity of the ground-based real-time monitoring.

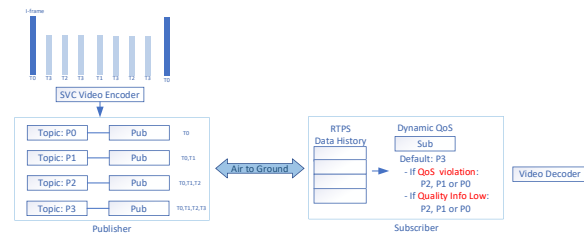


Fig. 6. QoS-aware dynamic content publish using PartitionQoS strategy.

For telemetry data, the same strategy can be applied. Critical safety data that must be guaranteed can be assigned to a low-bitrate sub-stream, ensuring that key information remains transmittable even during temporary degradation of the air-to-ground communication link. Subsequently, when link quality recovers, the system can automatically and dynamically adjust the transmitted information sub-stream, thereby establishing a more robust transmission performance.

5. Conclusion

Based on the technical requirements for flight test data acquisition and air-to-ground data transmission, this paper proposes the integration of Data Distribution Service technology into flight test systems. This approach enables a data-centric publish-subscribe paradigm, establishing a data bus for efficient data transmission and a management bus for device and station control. A reference architecture for a Flight Test RAN is constructed, wherein station management and operational control data are shared over the Air-to-Ground wireless transmission link as ancillary information. By configuring differentiated QoS policies, a comprehensive networked air-ground system architecture for flight test monitoring and management is formed. This solution supports multi-ground-station and multi-aircraft flight test operations, allowing flexible dynamic expansion, seamless integration of ground stations, and compatibility with heterogeneous transmission network equipment. It ultimately constitutes an integrated air-space-ground flight test network transmission system.

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