D5.4: REPORT ON L-BAND DIGITAL AERONAUTICAL COMMUNICATIONS SYSTEM RESEARCH

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EXECUTIVE SUMMARY

This report corresponds to D5.4 Report on L-band digital aeronautical communications system research. The work reported is related to WP5.3 Research on L-band digital aeronautical communications system to support air ground data exchange.

WP5.3 is organized in two different tasks:

- Task 5.3.1 Requirements Analysis of LDACS Supporting 4D Trajectory Based Operations
- Task 5.3.2 Architecture Design of Onboard LDACS
- Task 5.3.3 Development of Data Link Subsystem supporting LDACS

Deliverable D5.3 covers the work performed in both Task 5.3.1 and Task 5.3.2.

The information contained in this report includes the requirements analysis of LDACS in the 4D trajectory based operation scenarios, and the overall architecture design of LDACS covering data link applications, data link protocol stacks as well as onboard communication devices. The LDACS concepts and capabilities are studied. The requirements of LDACS are captured from the perspectives of functionality, performance, safety and application. The system architecture of LDACS is designed by analyzing interfaces of the data link and other avionic systems. Finally, the added value which LDACS provides to stakeholders and end users is analyzed. This report provides theoretical supports and inputs for the development of data Link subsystem supporting LDACS in Task 5.3.3.

No major issues or deviations are to be reported.

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GLOSSARY

Acronym	Signification
4DT	Four Dimensional Trajectory
A/G	Aircraft/Ground
ACAS	Airborne Collision Avoidance System
AC-R	Access-Router

ADS-C	Automatic Dependent Surveillance–Contract
ANI	Airborne Network Interface
ANSP	Air Navigation Services Provider
AOC	Airline Operation Center
APNT	Alternative Position, Navigation and Timing
ARQ	Automatic Repeat-request
AS	Aircraft Station
ATC	Air Traffic Control
ATM	Air Traffic Management
ATN	Aeronautical Telecommunication Network
ATS	Air Traffic Services
AVI	Airborne Voice Interface
CCCH	Common Control Channel
CNS	Communication Navigation Surveillance
CPDLC	Controller Pilot Data Link Communication
CS	Convergence Sub-layer
CSP	Communication Service Provider
DC slot	RL slot carrying Dedicated Control Channel (DCCH) information
DCCH	Dedicated Control Channel
DCH	Data Channel
DFMC	Dual-frequency Multiconstellation
DLS	Data Link Service
DME	Distance Measuring Equipment
DME	Distance Measuring Equipment
EFB	Electronic Flight Bag
EGIS	Environmental Geographic Information System
EPP	Extended Projected Profile
FANS	Future Air Navigation System
FCI	Flight Control Indicator
FDD	Frequency Division Duplex

FL	Forward Link
FL/BC slot	MAC slot occupied by FL broadcast (BC) frame (comprising BC1+BC2+BC3 sub-frames)
FL/CC slot	MAC slot occupied by the FL Common Control (CC) frame
FMS	Flight Management System
GBAS	Ground-Based Augmentation System
GLONASS	Global Orbiting Navigation Satellite
GNSS	Global Navigation Satellite System
GNSS	Global Navigation Satellite Systems
GPS	Global Position System
GS	Ground Station
GSC	ground-station controller
GSM	Global System for Mobile Communications
ILS	Instrument Landing System
IPS	IP protocol suite
IWF	Interworking Function
JTIDS	Joint Tactical Information Distribution System
LDACS	L-Band Digital Aeronautical Communications System
LLC	Logical Link Control
LME	LDACS Management Entity
MAC	Media Access Control
MIDS	Multi-Function Information Distribution System
MIDS	Multi-Function Information Distribution System
NAVIDS	Navigation Identification System
OFDM	Orthogonal frequency-division multiplexing
OFDMA-TDMA	Orthogonal Frequency Division Multiple Access- Time Division Multiple Access
OSI	Open System Interconnect
PDU	Protocol Data Unit
PHY	Physical
QoS	Quality of Service

RCU	Radio Control Units
RL	Reverse Link
RL DC slot	MAC slot providing a transmission opportunity for RL Dedicated Control (DC) segment
RSBN	Short-range radio navigation system
SAC	Sub-net Access Code
SDU	Service Data Unit
SNDCF	Sub-Network Dependent Convergence Function
SNP	Sub-Network Protocol
SSR	Secondary Surveillance Radar
SWIM	System Wide Information Management
TBO	Trajectory Based Operations
TDD	Time Division Duplex
UAT	Universal Access Transceiver
UMTS	Universal Mobile Telecommunications System
VDL	Very High Frequency Data Link
VHF	Very High Frequency
VU	Voice Unit

1. INTRODUCTION

1.1. PURPOSE OF THE DOCUMENT

This document provides the Report on L-band digital aeronautical communications system research within GreAT MWP5- Supporting avionic system. It describes the requirement analysis and architecture design of L-band digital aeronautical communications system (LDACS) supporting 4DT-based operation.

1.2. INTENDED READERSHIP

The intended audience for this document are all the partners involved in GreAT including Commission Services.

1.3. STRUCTURE OF THE DOCUMENT

This document describes the requirements analysis of LDACS in the 4D trajectory based operation scenarios and the overall architecture design within GreAT project MWP5-Supporting avionic system.

The structure of the document is as follows:

- **Chapter 1 "Background"** introduces the scenario of 4DT-based operation, the evolution process of LDACS and its advantages;
- **Chapter 2 "Research on LDACS technologies"** describes the technical specification of LDACS, including its capabilities, coverage, topology and frequency specification, and describes the overall architecture design covering the physical layers, protocols and interfaces
- **Chapter 3 "LDACS system features and other requirements"** describes the system features of LDACS airborne equipment and ground equipment, as well as the performance, safety and application requirements of LDACS;
- **Chapter 4 "Upgrade scheme of LDACS replacing VHF"** describes the scheme of upgrading the existing VHF communication system by adding additional LDACS data links;
- **Chapter 5 "Added value for stakeholders and end users"** describes the added value LDACS provides to the following three different stakeholders and end users: airlines and airspace users, ANSP (Air Navigation Services Provider) and CSP (Communication Service Provider).

2. BACKGROUND

4DT operation begins with the basic 4DT negotiated by airspace users and air traffic service providers, which takes into account the interests of users and the constraints of airspace and airport capabilities. After being recognized by all parties, the basic 4DT can be used as the basis of actual flight operation. During actual flight operation, the airborne FMS (Flight Management System) optimizes and predicts the accurate 4DT of the aircraft according to the basic 4DT, combined with the aircraft performance characteristics and meteorological conditions, and sends the constructed accurate 4DT to the ground ATC (Air Traffic Control) system through the data link. The ground ATC system can detect the conflict between planned tracks of aircrafts as early as possible, and then conduct an air-ground 4DT negotiation with aircrafts through data link, so as to obtain an optimal flight profile that can avoid the conflict between aircraft and ground control restrictions. Finally, the airborne FMS accurately controls the speed through the 4D flight guidance to realize the automatic flight of the 4D track, and the whole flight process is monitored by the ground and the air.

It is pointed out that the modern ATM (Air Traffic Management) technology needs to change from voice communication to digital communication. The increasing and complex information exchange needs between the ground control center and pilots need modern communication technology as the support. At present, almost all air traffic consoles and pilots use voice to communicate with each other, but obviously, one disadvantage of voice communication is its high "overhead" and it is not suitable for efficiently transmitting air-ground interactive information. Although voice communication is reliable, its spectrum efficiency is very low, and usually only a few data bits can be used to represent the content of the message. To cope with this issue, it is necessary to develop digital communication links. Theoretically, the digital communication link can obtain the best coverage when it works in VHF (Very High Frequency) band. Actually, ICAO established a VHF data link: VDL (VHF Data Link) more than 20 years ago, but the throughput of this link is too low to meet the application scenarios of ATM in the future, so it is necessary to develop a new data link standard. LDACS (L-band Digital Aeronautical Communications System) is a high-capacity data link supporting mobile communication, which involves the flight safety and regularity of all airspace (such as air routes, terminal airspace and airports). This kind of data link works in L-band (960 MHz ~ 1164 MHz), which overcomes the disadvantage of low throughput of VHF data link and meets the requirements of data communication between aircraft and the ground during route flight.

As a modern aviation data link, LDACS has the following advantages compared with traditional data link technologies:

1. Scalability. Scalability is the key to low-risk implementation of LDACS technology. This critical feature allows LDACS to be deployed step by step in existing systems with very low risk. LDACS can initially be used as a deployment of existing infrastructure to supplement the system and gradually replace the traditional VHF (Very High Frequency) data link. LDACS uses the standard IP interface, so it can be easily integrated into the existing communication infrastructure.

To support future services, LDACS can provide data throughput of 550 kbit/s to 2.6 Mbit/s according to the selected adaptive coding and modulation scheme. This is 50 to 200 times higher than the throughput of the currently operating VDL (VHF Data Link) Mode 2 system. LDACS can also manage service priority, thus ensuring bandwidth, low latency and high continuity services, which are used for safety-critical applications, and can also accommodate AOC (Airline Operation Control) services. In addition, LDACS can provide secure private communication between aircraft operators and ANSP (Air Navigation Services Provider). These capabilities provide LDACS with strong scalability.

2. Simultaneous communication and navigation. In addition to communication capabilities, LDACS also provides navigation functions. The location data is similar to DME (Distance Measuring Equipment) and is extracted from LDACS communication link between aircraft and LDACS ground station. This gives LDACS the ability to provide APNT (Alternative Position, Navigation and Timing) to supplement the existing airborne GPS (Global Position System) without additional bandwidth. As far as operation is concerned, it makes no difference whether the navigation data is provided by LDACS or DME. This case is similar to ILS (Instrument Landing System), and GBAS (Ground-based Augmentation System) is an alternative to the precise method, with minimal impact on flight procedures, pilot interface and training.

Unlike today, LDACS provides enhanced data transmission capability, and enhances DFMC (Dual-frequency Multiconstellation) GBAS2 by providing additional enhancement information. LDACS also supports future network security measures of GBAS, such as authentication and information integrity, which will help to enhance the resilience and security of this critical flight navigation application. In addition to GBAS, LDACS also provides safe and increased throughput, which lays a foundation for future navigation applications, such as precise bending method and complete 4D orbit operation.

3. High efficiency of embedded spectrum. Spectrum is a scarce and valuable resource, especially in the aviation L-band, which has been allocated many very important services. LDACS has high spectrum efficiency because it is designed to be placed in these areas of L-Band. Until now, other services cannot be allocated in these areas.

The high efficiency of LDACS spectrum utilization is realized by designing LDACS, which can coexist with DME in L-band. LDACS uses interference mitigation algorithm to deal with the interference from DME. In addition, LDACS out-of-band radiation has been minimized to protect DME and other existing L-band systems. This is a new function of data link system, which provides LDACS with a unique feature to support efficient spectrum allocation process.

LDACS is designed as a cellular system. Therefore, by allocating different frequencies to adjacent LDACS units, the known common channel interference of VDL (VHF Data Link) mode 2 is avoided.

4. Security. Aviation needs secure data and voice information exchange to manage the safe air traffic flow in the global airspace. Till now, the main communication method of ATC is still the open analog voice broadcast in aviation VHF band. At present, information security is entirely based on procedures, trained personnel and verified communication procedures. This communication method has been used since 1948. Future digital communication waveforms will require additional embedded network security features to meet modern information security requirements, such as authentication and integrity. The security features of these networks need sufficient bandwidth, which is beyond the capability of VHF narrow-band communication system.

For voice and data communication, sufficient data throughput capacity is needed to support network security features, while not degrading performance. LDACS is a mature data link technology with sufficient bandwidth to support network security. Since the development process, LDACS has realized network security through design, and achieved the standardized network security objectives of ICAO.

3. RESEARCH ON LDACS TECHNOLOGIES

LDACS provides two operation models, one for air-to-ground communication and the other for air-to-air communication. The two models use different radio channels and adopt different methods of physical layer and data link layer.

In these two modes, LDACS must cooperate with existing aviation L-band systems (DME, JTIDS (Joint Tactical Information Distribution System) /MIDS (Multi-Function Information Distribution System), UAT (Universal Access Transceiver), GNSS (Global Navigation Satellite System)) and systems close to aviation L-band (such as GSM (Global System for Mobile Communications) /UMTS (Universal Mobile Telecommunications System)). LDACS aims to minimize the interference to and from these systems. The specific interference in L-band affects the decision-making related to LDACS system design.

3.1. MAIN CAPABILITIES OF LDACS

LDACS is a multi-application cellular broadband system derived from 4G technology, which can simultaneously provide various air traffic services (including ATS-B3) and Airline Operation Control (AOC) communication services from ground station (GS). The physical layer and data link layer of LDACS A/G subsystem are used for data link communication, but the system also supports air-ground voice communication.

LDACS supports all airspace and airport ground communication.

Physical LDACS unit coverage is actually decoupled from the service coverage required by a specific service. Services requiring extensive coverage are installed in several adjacent LDACS units. The handover between LDACS units involved is seamless, automatic and transparent to users. Therefore, the communication concept of LDACS A/G is open to the future concept of dynamic airspace management.

The LDACS A/G subsystem provides two-way point-to-point processing data links, including Forward Link (FL) and Reverse Link (RL) and optional broadcast function (FL only). The LDACS data link subsystem (AS and GS) can be integrated into the Aeronautical Telecommunication Network (ATN) through the access router as a subnet, and support data transmission based on ATN/IPS and ATN/OSI protocol stacks. The system is controlled by the ground-station controller (GSC), as shown in Fig. 3-1.

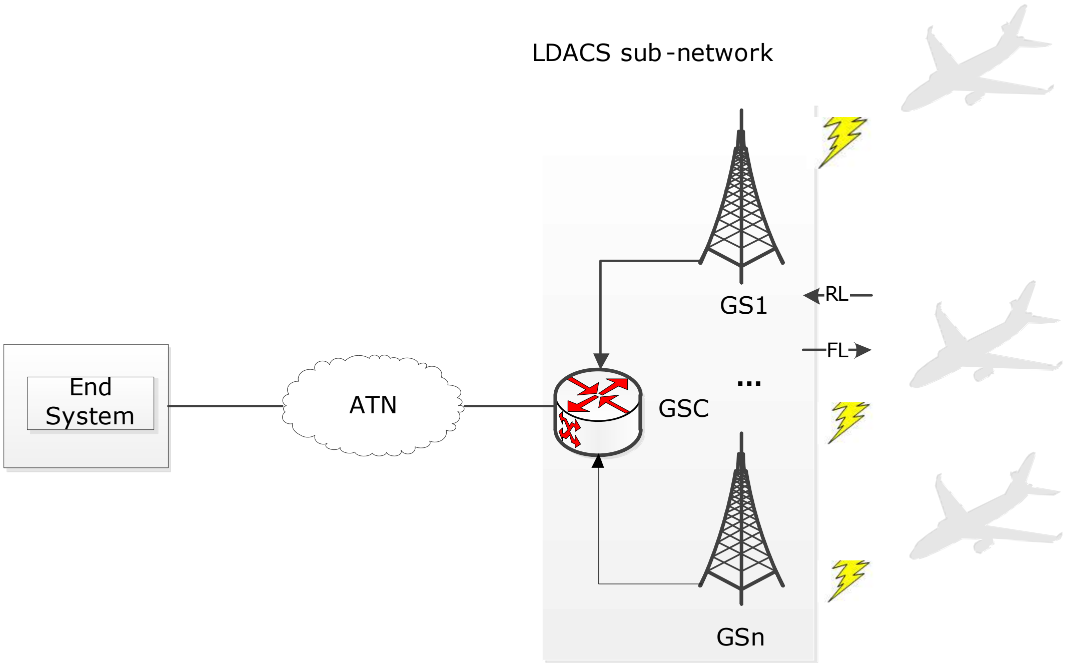

Fig. 3-1 : LDACS subnet connection diagram

Besides communication, LDACS system can also be used for ranging, which can provide input for APNT scheme.

The "2011 White Paper on Global Environment Geographic Information System (EGIS)" pointed out that GNSS is the core technology of single-point troubleshooting in aviation industry. In the new year, the aviation industry will gradually eliminate the traditional NAVIDS (Navigation Identification System), strengthen technical innovation and introduce more advanced and intelligent basic communication equipment.

The LDACS-NAV signal modulation scheme weakens the spectrum issue of DME/eDME scheme. As LDACS-NAV is an L-band signal based on ground communication, it has perfect built-in navigation feature and IP-based data link solution. At present, LDACS-NAV consists of cellular network of orthogonal frequency-division multiplexing (OFDM) network, and its working principle is to monitor the opportunity signal in the communication switch, and then calculate the air positioning according to the signals of several ground transmitters. During this process, the signal is secure protected by L band in real-time . The interference mitigation algorithm from the ground station can also greatly reduce the out-of-band radiation and ensure the security and stability of DME signals.

It has proved that this solution has the advantages of efficient and safe spectrum, no need for additional signal bands, and expandable local demand of the unit. In addition, LDACS-NAV also has the functions of point-to-point ranging in the air, real-time monitoring and enhancing DFMC GBAS, etc., and can send navigation information to auxiliary equipment to generate planar trajectory or 4D trajectory of aircraft. Therefore, LDACS-NAV signal is more recognized by aeronautical research.

Companies such as Frequentis AG and Leonardo SpA have established full-featured LDACS interoperability models. In March 2019, the German Aerospace Center (DLR) conducted a performance test for LDACS, and the results showed that LDACS-NAV still met the international standard of RNP 0.3 in the low altitude environment below 10 m.

At the end of 2020, the ICAO standardization group has started the guidance of LDACS communication and navigation. If all goes well, LDACS-NAV will be officially applied to enhanced DME system in the near future.

3.2. LDACS COVERAGE

The maximum design coverage of LDACS in conventional range mode is 200 nm (200 nautical miles, or 370 km). In practical engineering, the design coverage is determined by the propagation protection time considered in the system design process. The actual operation coverage can be selected as less than 200 nm, depending on the actual interference. LDACS can also be switched to extended range mode by using directional antennas, and the maximum coverage under this mode can reach 400 nm.

3.3. LDACS TOPOLOGY

LDACS running in A/G mode is a cellular point-to-multipoint system. The LDACS GS is a centralized instance that controls the LDACS A/G communication in its cell. LDACS GS can simultaneously support both-way communications with multiple ASs under its control. The LDACS ground station is connected with the ground-station controller (GSC) that controls the LDACS subnet. The topology of LDACS is shown in Fig. 3-2.

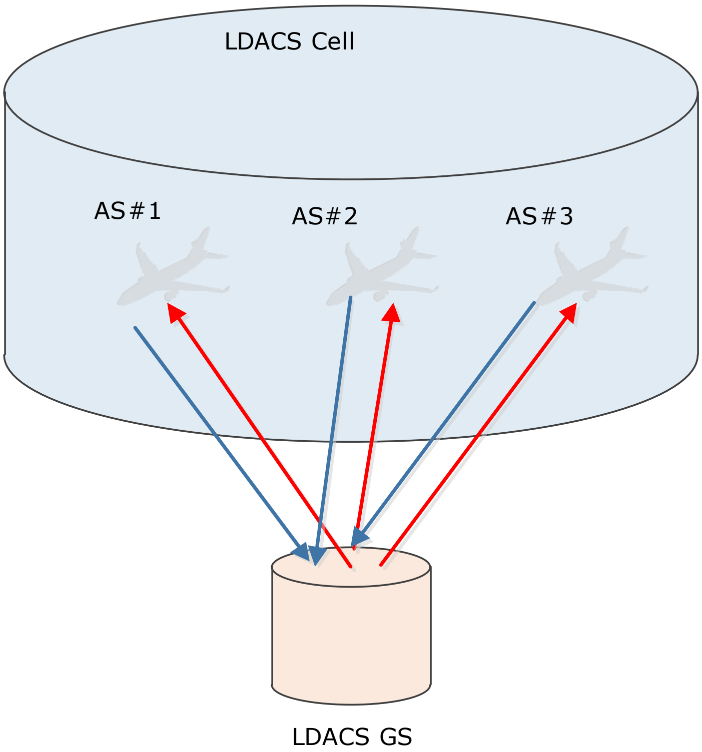

Fig. 3-2: Topology diagram of LDACS (in a single cell)

Before using the system, the AS must register in the control GS to establish a dedicated logical channel for users and control data. The control channel has allocated resources statically, while the user channel has allocated resources dynamically according to the current demand. The logical channel only exists between GS and AS.

3.4. LDACS FREQUENCY SPECIFICATION

The LDACS operates in the lower part of the L-band (960-1164 MHz), and will not interfere or affect the interference of the existing L-band system. At present, several other systems have been running in L-band.

Distance Measuring Equipment (DME) runs on the Frequency Division Duplex (FDD) system on the 1 MHz channel grid, and is the main user of L-band. In some countries, military Multi-function Information Distribution System (MIDS) uses a part of this frequency band. Several fixed channels are allocated to

Universal Access Transceiver (UAT), Secondary Surveillance Radar (SSR) and Airborne Collision Avoidance System (ACAS). Global Position System (GPS), Global Orbiting Navigation Satellite System (GLONASS) and GALILEO made a fixed frequency allocation in the upper part of L-band. Commercial systems of Universal Mobile Telecommunications System (UMTS) and Global System for Mobile Communications (GSM) operate below the lower boundary of aviation L band (960 MHz). In addition, in some parts of the world, different types of RSBN (Short-range radio navigation system) systems may be found between 960 MHz and 1164 MHz.

The LDACS frequency band of A/G link is as follows:

1. Forward link (FL): 1110-1156 MHz
2. Reverse Link (RL): 964-1010 MHz

The occupied bandwidth of LDACS signal is Bocc = 498.05 kHz.

The LDACS channel allocation is shown in Table 1.

Table 1: LDACS channel allocation

LDACS channel	Center Frequency
LC#0	960.0 MHz
LC#1	960.5 MHz
LC#2	961.0 MHz
…	…
LC#8	964.0 MHz
…	…
LC#100	1010 MHz
…	…
LC#330	1125 MHz
…	…
LC#392	1156 MHz
…	…
LC#408	1164.0 MHz

3.5. LDACS INTERFERENCE MITIGATION METHOD

DME is the main equipment in the system using L-band. In order to deal with the possible interference in L-band, LDACS has certain specifications on the equipment level. The LDACS receiver should be able to receive the required LDACS signal in the presence of other L-band signals with high power, but this capability needs to be highly dependent on the frequency offset between the target and non-target channels. The bandwidth of LDACS radio frequency is set to a trade-off value between system transmission capacity and DME channel. Besides, the system also needs to take appropriate interference mitigation methods. Here are some available methods:

1. Erasure Decoding. This method needs to measure the received interference power in the guard band of FFT (Fast Fourier Transform) bandwidth. According to the measured interference power in the guard band and the spectrum shape of the interference, the interference power at the data sub-carrier can be approximately calculated. If the approximate interference power exceeds a predefined threshold, the affected symbol in the index (k, m) should be set to "Erase". Setting "Erase" means that the reliability information of the inherited coded bits in this data

symbol will be set to 0 at the input of the convolutional decoder. The threshold is a function of the average OFDM (Orthogonal frequency-division multiplexing) symbol power at the receiving end. This threshold will need to be adjusted if the pulse blanking method is also applied.

2. Oversampling. This method suggests that the received time domain signal should be oversampled at least 4 times. Because the interference signal power may be high, RX channel filtering may not completely eliminate the out-of-band interference power. When FFT is applied in OFDM receiver, these unwanted signal parts will periodically and repeatedly fall into the used frequency spectrum, which is related to the inherent properties of FFT-related samples. Therefore, in OFDM receiver, the downsampling of the original grid should be done after FFT.
3. Pulse blanking. Pulse blanking can mitigate the interference from the existing L-band system. This method must detect the interference pulses in discrete time domain, and these samples will be set to zero as long as the values of the corresponding samples in the RX signal exceed the threshold. After that, the modified RX signal can be converted to frequency domain according to normal operation. The threshold can be set to an intermediate value that can reduce the interference power without affecting the desired signal. If other interference mitigation methods (such as erasure decoding) are applied, the threshold may need to be adjusted.

3.6. DESIGN OF PHYSICAL LAYER

In order to maximize the capacity of each channel and make the best use of the available spectrum, LDACS is defined as an OFDM-based FDD system, which supports the synchronous transmission of Forward Link (FL) and Reverse Link (RL) channels, and the occupied bandwidth of each channel is 498.05 kHz. Within this bandwidth, 50 OFDM sub-carriers are placed with an interval of 9.765625 kHz. Each sub-carrier is modulated separately, and the total duration of each modulated OFDM symbol is Ts = 120 μs. OFDM parameters have been selected according to the specific conditions of aviation mobile L-band channel.

Although the Time Division Duplex (TDD) method is easier to implement, the TDD method will incur a large overhead and require a long guard interval because the system has to work over a long distance. Another advantage of FDD is that forward (ground-to-air) and reverse (air-to-ground) links can be aligned with DME uplink and downlink frequencies, which will greatly reduce coexistence constraints.

LDACS FL PHY is a continuous OFDM transmission. User data for broadcasting and processing are transmitted through the (logical) data channel, while dedicated control and signal information are transmitted through the (logical) control channel.

The LDACS RL transmission is based on OFDMA-TDMA bursts, and there is a silent phase between such bursts. RL resources are allocated by the Ground Station (GS) to different users (AS) on demand.

The LDACS A/G design includes propagation protection time sufficient to perform the operation within the longest distance of 200 nm (nautical miles) from the ground system. At this distance, the one-way propagation delay is 1.26 ms, which roughly corresponds to the duration of 10 LDACS OFDM symbols. In actual deployment, LDACS can be designed for any range up to this maximum range.

3.7. LDACS PROTOCOL ARCHITECTURE

The protocol architecture diagram of LDACS is shown in Fig. 3-3, which defines five main functional blocks above the PHY layer:

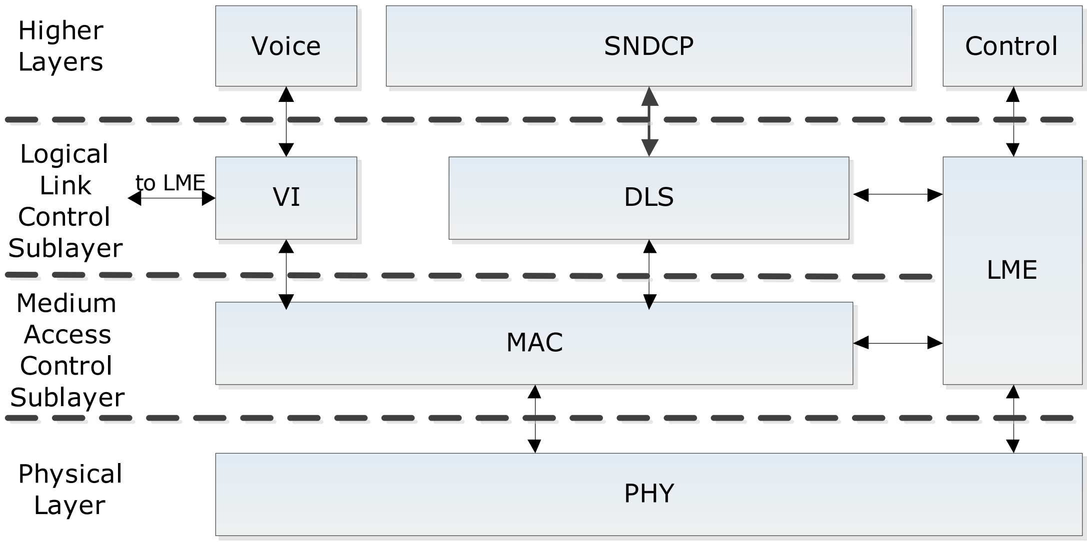

Fig. 3-3: LDACS protocol stack

Among them, four are located in the data link layer (DLL) of AS and GS:

1. LDACS Management Entity (LME)
2. Data Link Service (DLS)
3. Voice Interface (VI)
4. Medium Access Control (MAC)

One entity is located in the sub-network layer:

1. Sub-Network Protocol (SNP)

The LDACS network is externally connected to the voice unit, the radio control unit and the ATN network layer through the dependent Sub-Network Dependent Convergence Function (SNDCF), Convergence Sub-layer (CS) and Interworking Function (IWF) not discussed herein.

AS shown in Fig. 3-4, SNP connects the data link layer of AS and GS, providing the end-to-end user level connection between LDACS AS and GS.

The data link layer provides Quality of Service (QoS) guarantee according to the requirements of [COCRv2]. Different service classes can be reused. Except for the initial aircraft unit entry and type I handover, the transfer is decisive and has predictable performance. It also provides optional support for adaptive coding and modulation. The four functional blocks of LDACS data link layer are divided into two sub-layers, namely, Media Access Control (MAC) sub-layer and Logical Link Control (LLC) sub-layer, which will be discussed below.

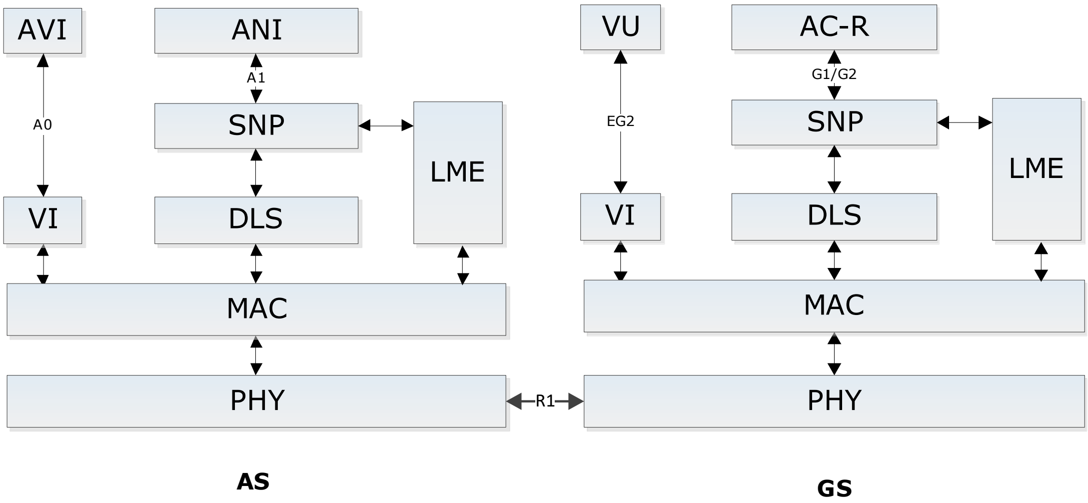

Fig. 3-4: LDACS air-ground interface

The AS is connected to the Airborne Voice Interface (AVI) and the Airborne Network Interface (ANI). GS is connected to the Voice Unit (VU) for interconnection with external voice services, as well as Access-Router (AC-R) and ground-station controller (GSC).

3.8. DESIGN OF MEDIA ACCESS CONTROL (MAC) SUB-LAYER

The media access control sub-layer includes a Media Access Control (MAC) entity. MAC entities exist in AS and GS. MAC entities will create logical channels between peer DLL entities, as shown in Fig. 3-5.

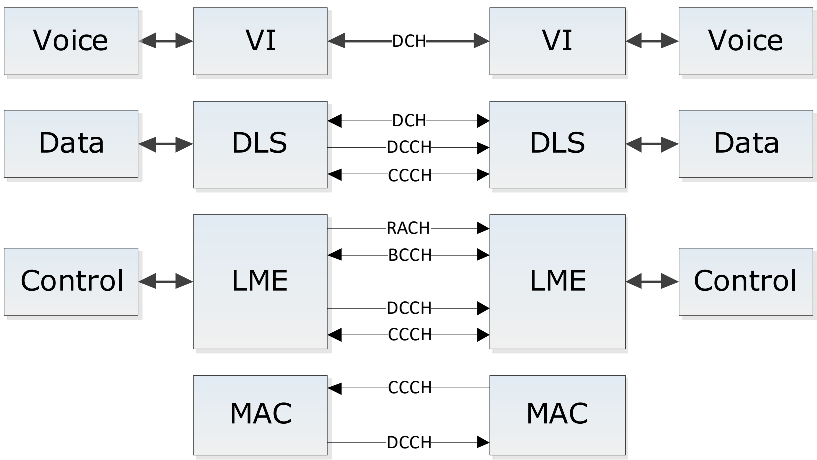

Fig. 3-5: DACS logical channel

The logical channels of DCH (Data Channel), CCCH (Common Control Channel) and DCCH (Dedicated Control Channel) are point-to-point channels, and each controllable AS has a corresponding DLS instance in GS.

The access to the PHY layer is managed by the MAC entity and realized by the slot structure built in PHY-PDUs. MAC slots can transfer different logical channels. Note that the FL slot structure has changed compared with the multi-frame structure. Slots are built by FL and RL PHY-PDUs, respectively. Every four FL data slots will be interrupted by a BC slot.

The sizes of the FL CC slot and RL CC slot can be dynamically adjusted (in the PHY-PDU step), so that the best conditions of different signal traffic can be achieved.

3.9. DESIGN OF LOGICAL LINK CONTROL (LLC) SUB-LAYER

The LLC sublayer in the data link layer manages the radio link and provides bearer services with different service classes to the subnet layer. It contains LME (LDACS Management Entity), DLS (Data Link Service) and VI (Voice Interface) entities. DLS and VI may appear in multiple instances.

There is one LME in each AS and one LME in GS. Under the control of NME, GS LME performs link maintenance and manages the cell-entry and cell-exit of AS in a specific GS and the handover between GS (mobility). During AS registration, GS will verify the identity and authorization of AS. This is done through BCCH (GS to AS) and RACH (AS to GS) logical channels. These two channels are special because they can be used by AS before registration. Otherwise, besides registration, LME uses CCCH and DCCH to exchange control information.

Dynamic allocation of physical layer resources to logical data channels is provided by GS LME. For ground-to-air transmission, this allocation is performed at the GS end. However, air-to-ground transmission resources must be requested by AS LME and allocated by GS LME. The air-ground resource allocation mechanism uses DCCH (AS to GS) and CCCH (GS to AS) logical channels to exchange resource requests and resource allocations.

Two-way exchange of user data between GS and AS is performed by DLS entity. There is one DLS entity in each AS, and there is one peer DLS entity in GS corresponding to each AS. All DLS entities use DCH logical channel for DLS user data transmission, and use DCCH and CCCH channels for DLS control data transmission.

LDACS provides built-in support for digital voice transmission. This service is provided by VI entity, and voice stream is transmitted through DCH logical channel. Channels can be shared by multiple users to simulate party-line voice communication. If multiple voice channels are to be provided simultaneously on a single LDACS radio channel, LME will select the logical voice channel to be used through VI (in this case, LME is controlled by an external system).

3.10. LDACS PROTOCOL STANDARD

The following are the relevant standards of critical functional blocks in LDACS protocol.

3.10.1. LDACS MANAGEMENT ENTITY (LME)

LME supports LDACS configuration, resource management and mobility management.

LME specifically provides the following services:

1. Mobility Management Service. The mobility management service supports login, logout, scanning adjacent cells, handshaking between cells, and managing AS addressing within cells. GS LME needs to coordinate with GSC in mobility management;
2. Resource Management Service. Resource management service provides link maintenance (power, frequency and time calibration), adaptive coding and modeling support, and user plane resource allocation;

The AS LME state transition is shown in Fig. 3-6.

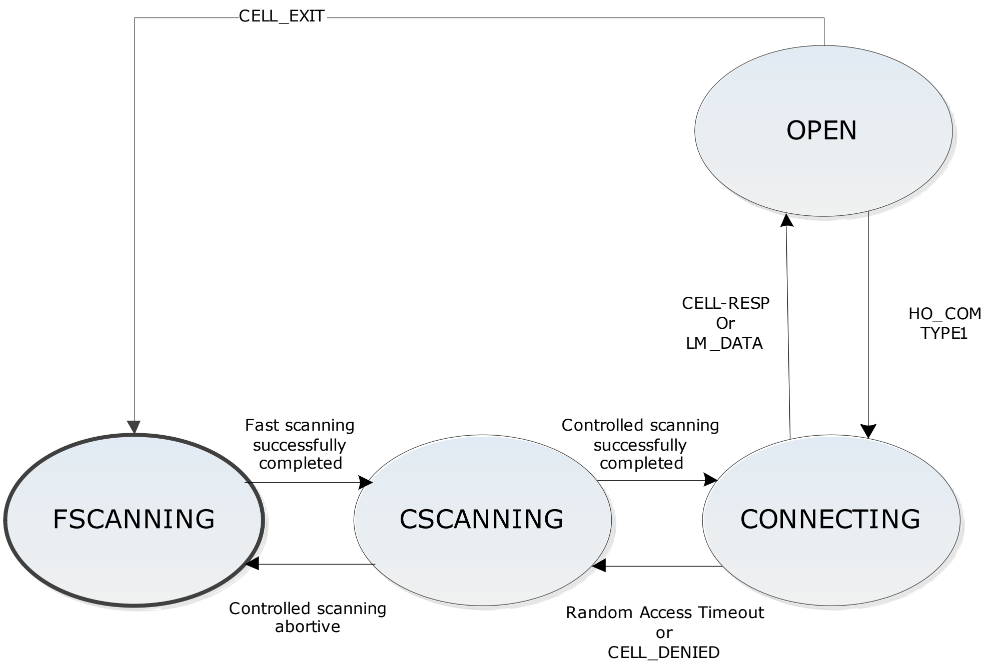

Fig. 3-6: LME state diagram

The LME enters the FSCANNING state after the airborne LDACS equipment is started. In this state, LME requests to trigger the MAC to scan quickly by calling MAC_FSCAN.req. After triggering, the MAC starts to automatically search for available LDACS channels. Once an available channel is found, the LME will command the MAC and itself to enter the CSCANNING state. Otherwise, LME will always be in FSCANNING state, which is always looking for channels.

After entering the CSCANNING state, the airborne LME performs the channel selection process by calling the MAC_CSCAN.req request. Through this request, the LME sends the list of preferred channels it has selected to the MAC. The LME then enters the CONNECTING state. When the MAC has executed the MAC_CONNECT.req request, the channel connection between AS and GS is established, LME enters the OPEN state, and LDACS communication between AS and GS is established. At this time, the data link application can use the interface provided by LDACS for air-ground communication.

LME provides the interface to accept the control of RCU, so that the administrator of airborne equipment can control and manage LDACS as needed.

The mobility management service in LME is supported by two broadcast control messages, namely, ACB (Adjacent Cell Broadcast) and STB (Scanning Table Broadcast). ACB can provide adjacent cell information, and STB allows AS to scan adjacent cells in the next broadcast control slot. The mobility management service provides a variety of functions, including Scanning, Cell Entry, Cell Exit, Addressing and Handover.

The resource management service provides functions such as Link Maintenance, Adaptive Coding and Modulation (ACM) and Resource Allocation.

3.10.2. MEDIA ACCESS CONTROL (MAC)

Media Access Control (MAC) is the lower sub-layer of Data Link Layer (DLL). It is the interface between Logical Link Control (LLC) sub-layer and Physical (PHY) layer, and LLC is the upper part of DLL. The MAC sub-layer relies on the PHY-PDU structure provided by the PHY layer to create the MAC slot structure, which is derived from but not equivalent to the PHY-PDU structure. This slot structure is used to provide logical channels for LLC entities. This is illustrated in Fig. 3-7. Note that the FL slot structure is shifted relative to the MF structure.

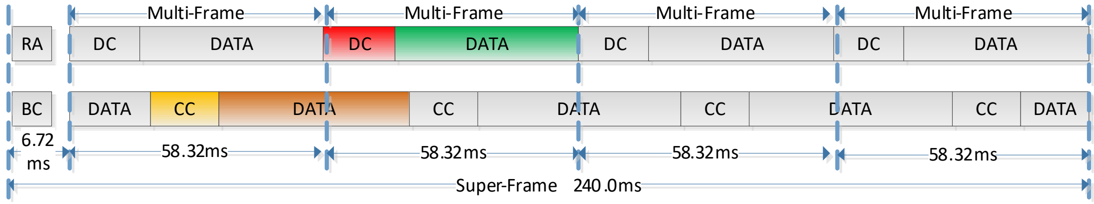

Fig. 3-7: LDACS MAC slot structure

The GS locally allocates FL channel resources (i.e. FL PHY-SDUs) in the slot structure and manages the access priority. RL uses an on-demand bandwidth scheme. The AS must request channel resources (RL PHY-SDUs) from the GS before transmitting data in the RL Data Channel (DCH). The resource request is sent to the GS through the Dedicated Control Channel (DCCH). Access to DCCH is certain, because each AS has a dedicated sub-slot (identified by control offset) in the DC slot that carries its DCCH. GS collects resource requests for DCH transmission from all ASs and calculates appropriate resource allocation. The resource allocation is notified to the AS through the Common Control Channel (CCCH). The AS that has received the resource allocation in the data slot can use the allocated PHY-SDUs to transmit DCH.

The MAC sub-layer supports the transmission of user data and control data on logical channels. The MAC of the AS must track the current RL PHY-SDU in each RL super-frame. With "RL PHY-SDU number", AS can recognize the slot signal and resource allocation, and know when to allow transmission. A similar method is implemented on FL (based on byte offset instead of PHY-SDU offset). In this way, the MAC of a specific AS can determine which FL data is used for that AS.

Services provided in MAC entities are as follows:

1. MAC Time Framing Service: it provides the synchronization function of MAC slot structure and physical layer framing. MAC time frame provides a dedicated time slot for each logical channel;
2. Medium Access Service: mapping the logical channel to the appropriate slot of PHY-SDUs to provide access to the physical channel for its service users;
3. Broadcast Control Channel (BCCH): BCCH is the logical channel of FL control level. GS uses it to notify cell configuration information and issue mobility management commands to AS. Only GS can be transmitted on this channel. MAC sub-layer maps BCCH to BC slot;
4. Random Access Channel (RACH)： RACH is the logical channel of RL control level. The AS uses it to request cell entry. Only AS can be transmitted on this channel. MAC sub-layer maps RACH to RA slot;
5. Common Control Channel (CCCH): CCCH is a logical channel of FL control level, which is used to notify AS of TDM layout (i.e. MAC slot layout) and resource allocation of FL and RL. In addition, GS uses it to transmit MAC and LLC control messages. Only GS can be transmitted on this channel, and MAC sub-layer maps CCCH to CC slot;
6. Dedicated Control Channel (DCCH): DCCH is the logical channel of RL control level. The AS uses it to transmit MAC and LLC control messages to GS. Each AS has its own DCCH, and no other entity can be transmitted on this channel except its own AS. MAC sub-layer maps DCCH to DC slot;
7. Data Channel (DCH): DCH is the logical channel of the user level. DCH is used to transmit DLS PDUs and VI PDUs of LLC sub-layer. DCH exists on RL and FL. MAC sub-layer maps DCH to FL or RL data slot.

3.10.3. DATA LINK SERVICE (DLS)

Data Link Service (DLS) sub-layer provides its users with two-way interaction of confirmed and unconfirmed user data (including packet mode voice). This service can be used by the Sub-Network Protocol (SNP).

The services provided by DLS are as follows:

1. Acknowledged Data Link Service. Support data transmission acknowledgment of Sub-Network Protocol (SNP). In order to achieve low latency and low overhead without loss of reliability, DLS

should adopt selective repeat ARQ, and perform transparent segmentation and reassembly according to the size of resource allocation.
The transmission acknowledgment function can ensure that DLS Service Data Units (DLS-SDUs) are transmitted in the correct order without duplication. In case of transmission error, DLS will start repeat. The segmentation and reassembly functions should be responsible for the encapsulation and unpacking of DLS-SDUs in DLS Protocol Data Units (DLS-PDUs). If DLS-SDU must be segmented (for example, due to the mismatch between the resource allocation size and DLS-SDU size), the segmentation and reassembly functions should be transparent to the acknowledged transmission function.

If the Send Acknowledgment Transmission function receives an acknowledgment for a complete DLS-SDU, it will inform SNP of the successful transmission.
After the DLS_P_MaxRT repeat fails, the Send Acknowledgment Transmission function will give up the transmission of DLS-SDU and inform its upper SNP of the transmission failure.

2. Unacknowledged Data Link Service. Unacknowledged data transmission of SNP is supported. The unacknowledged transmission function shall transmit DLS-SDU without acknowledgement or repeating. The segmentation and reassembly functions should be responsible for the encapsulation and unpacking of DLS-SDUs in DLS-PDUs. If DLS-SDU must be segmented (for example, due to the mismatch between the resource allocation size and DLS-SDU size), the segmentation and reassembly function should be transparent to the unacknowledged transmission function.
3. Broadcast Data Link Service. Support the SNP broadcast data transmission. The broadcast transmission should be addressed to the broadcast AS SAC, otherwise the broadcast transmission function is the same as the unacknowledged transmission function.
4. Packet Mode Voice Service. Voice packets (such as VoIP) are supported. The packet mode voice service has the same functionality as the unacknowledged transmission, but it has a reserved class of services in the DLS.
5. Classes of Service. Provide different levels of services. Service classes can be directly mapped to priorities. GS should use the requested service level to determine the order and size of resource allocation. In DLS, service classes are used to determine the priority of concurrent service requests in priority order.

3.10.4. SUB-NETWORK PROTOCOL (SNP)

SNP provides the end-to-end connection between AS and GS in LDACS subnet, and provides the basis for A1, G1, G2, G3, G4, G5, G7 and G8 interfaces.

SNP protects the GSC-configured communication by encryption, compresses IPv6 header, verifies the integrity of packets, and provides the routing of packets according to the service level of packets.

Services provided by SNP are as follows:

1. Data Link Service: It provides the functions needed to transmit user level data and control level data through LDACS subnet, and provides the function of routing SNP-SDUs to the appropriate DLS service level according to the service level requested by them. It should be noted here that the service level is requested through the DSCP field of IPv6 header. If other network layers need to be supported, the data link service must be extended accordingly. Finally, it can also provide the function of separating data packets of user level from control level.
2. Security Service: It is also called encryption and integrity protection service, which provides the function of secure communication through LDACS subnet.
3. Header Compression Service: header compression service should be provided based on Robust Header Compression (RoHC) framework. Note here that RoHC is defined for IPv6 packets. Therefore, if other network layers need to be supported, additional header compression mode must be used to extend header compression service.

The data transmitted in SNP is called SNP-PDU, and each SNP-PDU contains an integer number of bytes of data. The format of SNP-PDU is shown in Table 2:

Table 2: SNP_PDU format

Field	Size	Description

CTRL	1Bit	Control data flag bit
NSEL	7 Bits	Network selector
MAC	128 Bits	Message authentication code
User Data	≤SNP_P_SDU constant	Variable length user data load

3.10.5. VOICE INTERFACE (VI)

The VI entity provides support for virtual voice lines. The voice line can be permanently set by GS (to simulate the traditional party line voice service) or created on demand.

VI provides the following services:

1. Dedicated Circuit Voice Service: It supports the transmission of party line voice on a dedicated voice channel. Voice service is provided for a specific party-line, and voice lines are not shared with other users outside the party-line. Access should be based on the principle of "listen-before-push-to-talk", and a dedicated voice channel must be configured through GS.
2. Demand Assigned Circuit Voice Service: It provides access to voice lines created on demand. Both GS and AS can request to create voice lines allocated on demand.

The overall function of VI is to define the processes and message formats that allow digital voice transmission over data channels. The establishment and removal of voice channels are all carried out by LME, and VI only provides transmission and receiving services.

The main functions of the voice interface include:

1. Voice transmission. VI needs to support effective transmission of digital and low bit rate coding based on voice channel. VI shall be able to notify users of the source of received voice messages.
2. Voice channel access. VI need to provide an interface for "push-to-talk" voice channel access. VI provides priority overload access for authorized ground users.

The VI first encodes the voice message before transmitting it. VI uses AMBE 4.8 kbps (version number AMBE-ATC-10B) codec algorithm for encoding.

The encoded voice message is encapsulated as VI-PDUs for transmission. Every VI-PDU contains the AS SAC addresses of three 20 ms sound samples and the message source. The VI-PDUs are transmitted through the FL and RL of the data channel.

The transmission queue of VI-PDU should provide buffer for the synchronous mapping of voice samples generated by AMBE ATCC10B vocoder to MAC frame structure. Since the average multi-frame length (60 ms) is a multiple of the sample length of the vocoder, if three voice samples are transmitted per multi-frame, long-term synchronization can be ensured. This is provided by the VI setup program in LME. If the GS on RL DCH correctly receives the VI-PDU, the VI-PDU should be relayed on FL DCH to simulate the party line voice channel. If AS VI currently receives VI-PDUs on FL DCH, it must not transmit voice samples on RL DCH.

When VI receives VI-PDU, it shall indicate the source of the encoded voice message to the service user. The source code of voice message is in the header of every VI-PDU.

The voice channel supports two access processes:

1. Push-to-talk access mode: the access of voice channel shall be managed by the listen-before-push-to-talk protocol supported manually. If the user requests voice channel access (i.e., presses the talk-listen button), the VI-PDUs containing vocoder frames will be transmitted through DCH. Please note that if the voice is continuously transmitted on the FL DCH of this voice channel, VI-PDUs will not be transmitted through the AS voice transmission function.
2. Priority access mode: Priority access to voice channels should only be provided in GS. Ground priority access should be realized by GS controlling the relay functions of FL DCH and VI-PDU.

If the privileged ground user requests to access the channel, the relay of the VI-PDUs received on the FL DCH should be preferentially carried out during the VI-PDUs transmission of the privileged users on the FL DCH. AS voice users should then be alerted that their voice access is rejected by GS, but in favor of preferred ground users.

The format definition of voice PDU is shown in Table 3:

Table 3: Voice PDU format

Field	Size	Description
AS SAC	12 Bits	Subscriber access code
PAD	36 Bits	Reserved
VOICE	288 Bits	Bit AMBE-ATC-10B vocoder samples

3.11. LDACS INTERFACE

The general interface of LDACS air-ground communication is shown in Fig. 3-8.

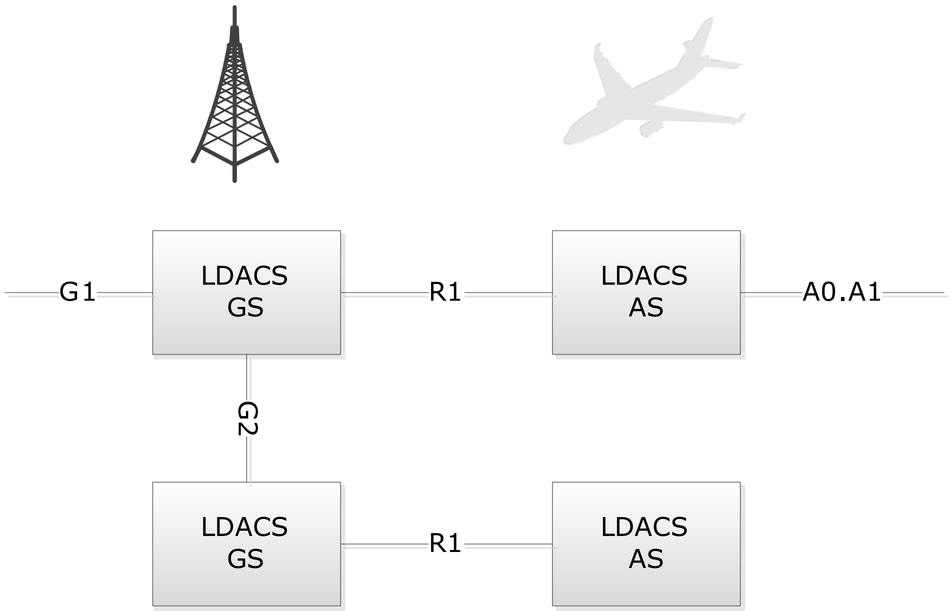

Fig. 3-8: LDACS subnet architecture and interfaces

LDACS A/G mode realizes the R1 interface in **Error! Reference source not found.**.Two-way data transmission between LDACS airborne system and LDACS ground system is provided. ATC oriented to 4DT mainly depends on the both-way communications between aircraft and ground ATC system, so the A/G mode of LDACS is the highlighted herein. In fact, the communication between aircraft, namely LDACS A/A mode, also sends data to the ground system first, and then the ground system forwards it to the target aircraft.

The following shows the communication interfaces between entities within the LDACS AS and LDACS GS.

3.11.1. LDACS AIRBORNE INTERFACES

Fig. 3-9 shows the interfaces of LDACS Aircraft Station. The interfaces in the red boxes are those provided by LDACS for external applications. The rest are the internal interfaces of LDACS Aircraft Station, which are used to provide internal data transmission service for the normal operation of LDACS.

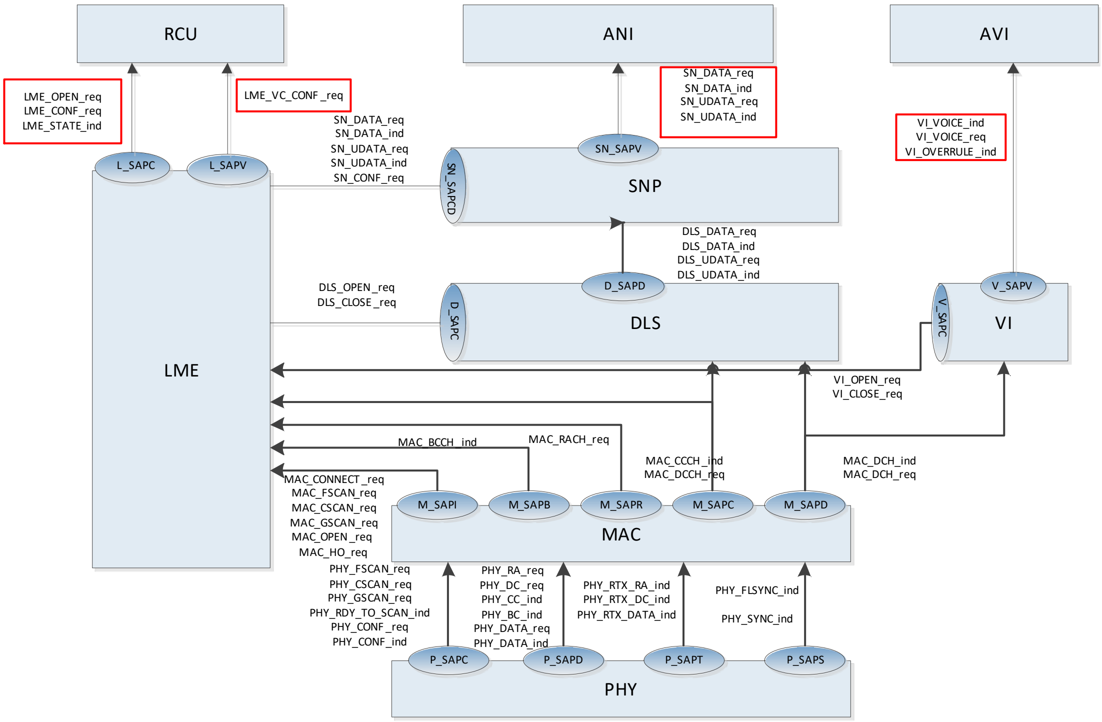

Fig. 3-9: Airborne LDACS interfaces

3.11.2. LDACS GROUND INTERFACES

Fig. 3-10 shows the interfaces of LDACS Ground Station. Similarly, the interfaces in the red boxes are those provided by LDACS for external applications. The rest are the internal interfaces of LDACS Ground Station, which are used to provide internal data transmission service for the normal operation of LDACS.

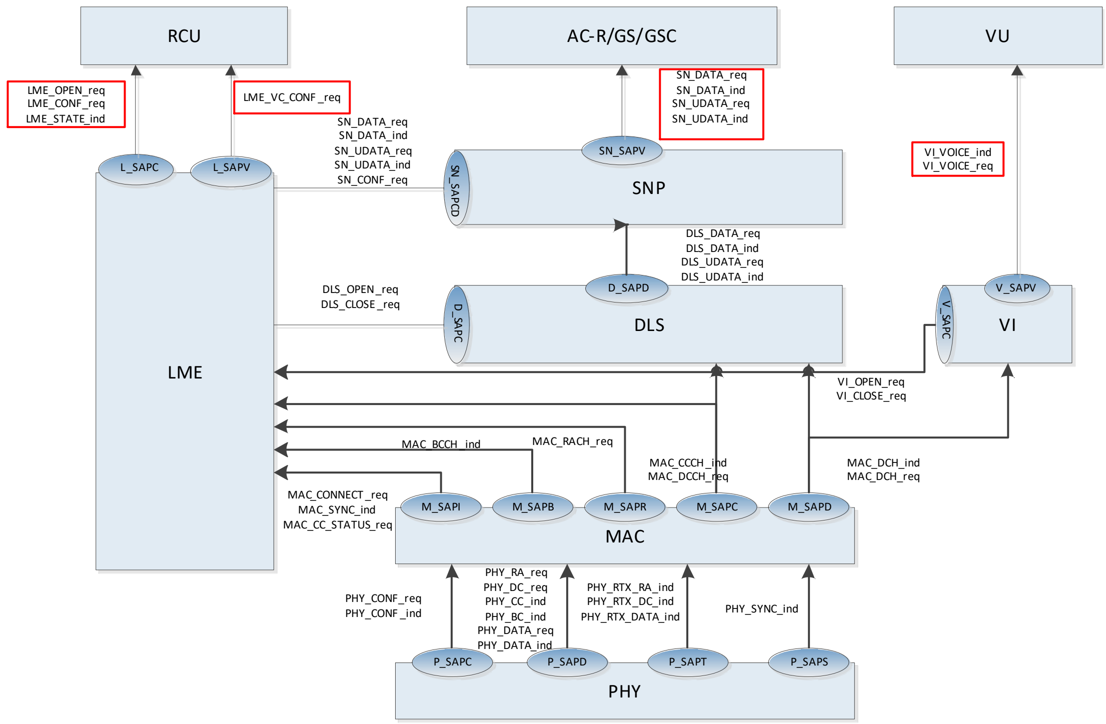

Fig. 3-10: Ground LDACS interfaces

4. LDACS SYSTEM FEATURES AND OTHER REQUIREMENTS

4.1. SYSTEM FEATURES OF AIRBORNE EQUIPMENT

1. The LDACS duplexer shall be of passband type;
2. The in-band insertion loss of LDACS AS duplexer should be less than 1 dB;
3. On the designated LDACS FL frequency band, the minimum attenuation of the AS duplexer from the sending port to the receiving port should be 69 dB at least;
4. The LDACS receiver should tolerate the peak pulse interference signal power of +30 dBm at its input without damage.

4.2. SYSTEM FEATURES OF GROUND EQUIPMENT

1. The insertion loss of LDACS transmitting and receiving filters should be less than 1 dB;
2. The LDACS transmitting and receiving filters shall provide mutually exclusive protection for other related systems;
3. LDACS GS should be mutually synchronized with finite synchronization error;
4. The synchronization error of LDACS GS network should be smaller than 1.6 µs;
5. If LDACS GS network provides ranging function, the synchronization error should be less than 50 ns.

4.3. PERFORMANCE REQUIREMENTS

1. LDACS should provide application support of CPDLC based on ATN-B1 and ATS/B2, and should also support ATS-B3 in the future;

2. LDACS should support ADS-C application;
3. The required communication performance of LDACS shall conform to RCP400/A2, RCP240 and RCP130, and also conform to RCP60 in the future;
4. The required monitoring performance of LDACS shall conform to RSP400/A1+A2, RSP180/D and RSP160/A1, and also conform to RSP60 in the future.

4.4. SAFETY REQUIREMENTS

1. LDACS shall provide the capability to ensure the availability and continuity of the system;
2. LDACS should provide the capability to protect the integrity of messages in transmission;
3. LDACS should provide the capability to protect the authenticity of messages in transmission;
4. LDACS shall ensure that the message in transmission has a unique source;
5. LDACS shall provide confidentiality/privacy capabilities for messages, including encryption and decryption mechanisms;
6. LDACS shall provide the capability of mutual authentication between airborne and ground subsystems;
7. LDACS should provide the capability to authorize the allowed behaviors to users;
8. If LDACS provides interfaces to multiple domains, LDACS should provide the capability to prevent intrusion into the domains and spread to external domains;
9. LDACS services should be protected from service attacks.

4.5. APPLICATION REQUIREMENTS

1. LDACS should support multiple service levels to provide appropriate service levels to applications;
2. If there is race condition, LDACS should preempt the services with low priority.

5. UPGRADE SCHEME OF LDACS REPLACING VHF

LDACS provides enhanced functions for the existing communication infrastructure. The following describes the scheme of upgrading the existing VHF communication system by adding additional LDACS data links.

Considering the current infrastructure and user groups of VDL Mode 2, combining the technical advantages of LDACS with the existing infrastructure of VDL Mode 2 can bring about a win-win situation. The capacity provided by LDACS is at least 50 times that of VDL Mode 2, which is an enhancement of the existing VDL Mode 2 business model.

The introduction of LDACS does not mean that the basic equipment of the aircraft must be modified a lot, and the existing space, antenna and interface can be reused. There is a multi-frequency method developed for VDL Mode 2, which can switch VDL Mode 2 radio to any frequency, including L-band. Therefore, LDACS/VDL radios can be combined in a single avionics device, and the previous VHF antenna can be replaced by a dual-band VHF/L-band antenna with the same floor area, so that the high-capacity bandwidth data link in the L-band can supplement the existing narrow-band VDL Mode 2 data link. As shown in Table 4.This method can reuse the infrastructure of VDL Mode 2, improve business efficiency and minimize investment risk.

Table 4: Combination of LDACS and VDL Mode 2

	LDACS (current)	VDL Mode 2 (current)	LDACS/ VDL Mode 2 combined avionics device (expected)

Applications and services	CPDLC, ADS-C and their future applications and services	CPDLC、ADS-C	CPDLC, ADS-C and their future applications and services
Spectrum availability	Reliable	Restricted	Reliable
Number of available channels	More	Average or less	More
Data rate per channel	Higher	Low	Higher
Existing service providers	Not yet available	Available	Available
Existing infrastructure	Not yet available	Available	Available
Existing users	Not yet available	Available	Available
Safety	Built-in function	Not available	Built-in function
Voice ability	Built-in function	Not available	Built-in function
Navigation ability	Built-in function	Not available	Built-in function
Long-term development capability	Higher	None	Higher

There are some technical challenges for combining two wireless radios into a multimode LDACS/VDL avionics device, such as heat dissipation or input current limitation. These can be solved by avoiding simultaneous transmission of LDACS and VDL data. Meanwhile, it is unnecessary to transmit both data simultaneously, because LDACS transmission can provide enough data throughput for all foreseeable applications. The receiver can listen to the data from both bands at the same time, and when a certain frequency band is available, it is configured as the corresponding receiving mode.

This step-by-step approach allows LDACS to be put into use quickly and to bring about benefits. With the deployment of more and more LDACS ground equipment, the frequency allocation mechanism of multimode LDACS/VDL radio will automatically select the communication frequency band. When LDACS equipment is fully deployed, VDL Mode 2 equipment can be decommissioned, and VHF spectrum can be used for other aviation applications.

6. ADDED VALUE FOR STAKEHOLDERS AND END USERS

LDACS provides added value to the following three different stakeholders and end users: airlines and airspace users, ANSP (Air Navigation Services Provider) and CSP (Communication Service Provider).

6.1. AIRLINES AND AIRSPACE USERS

LDACS has larger bandwidth and higher throughput, which provides better support for AOC data traffic, and is a technical driver for connecting aircraft operations. Large bandwidth plus data priority capability enable LDACS to reliably transmit a large amount of basic business data, such as graphic weather information, without interrupting the transmission of safety-critical ATC data traffic. These technical features also facilitate the frequent transmission of large engine and maintenance data, generating reusable value for airlines by supporting better fleet management and shortening aircraft turning flight time.

Because of its secure air-to-ground connection, LDACS is suitable for basic operational applications, such as EFB (Electronic Flight Bag). By meeting the standardized safety requirements of ICAO, LDACS reduces the network security risks by providing secure connections for flight decks and other safety-critical avionics devices, such as flight control and FMS (Flight Management System). These network security features are essential for today's flight operations, and are necessary drivers for advanced ATM and connected aircraft applications, such as business trajectory negotiation and 4D trajectory-based operations.

6.2. AIR NAVIGATION SERVICE PROVIDER

The future operation concept of ATM is based on a capable and reliable data communication infrastructure that can connect aircraft and ATM ground systems. This connectivity provides pilots and air traffic controllers with timely information about flight intentions and services provided through the ground system.

LDACS provides the capacity required to guarantee the quality of service on the secure communication link, and realizes services such as secure ADS-C, EPP, complete TBO and ATS/B2 CPDLC. LDACS will also provide services for emerging ATS/B3 services. Therefore, as a competent data communication backbone, LDACS is a prerequisite for integrating aircraft into SWIM environment, and can realize promising concepts in the future, such as flight-centered ATM.

It is expected that LDACS will become the main ground component of FCI multi-link infrastructure covering all flight phases. Once deployed, it will provide ATC and AOC services in and around the airport during taxiing, takeoff, approach and landing, as well as en route.

6.3. COMMUNICATION SERVICE PROVIDERS

The value chain of digital communication services covers multiple stakeholders. As CNS services gradually enter the category of regulated air navigation services, it will become more and more important to cope with the interface issues among the actors in the communication service supply chain to continue to ensure ATC to provide high-level services.

ATM is undergoing a fundamental change in concept. It is increasingly relying on a library of automated tools to help air traffic controllers and flight crews improve operational safety and productivity while allowing for improved traffic levels. This ultimately provides commercial benefits for airlines and ANSP. The improvement of automation depends on the air-ground data transmitted through CSP network.

At present, the air-ground connection for ATC purposes is provided through VHF media supporting ATN, in addition to several other media such as ACARS network. These media are basically media in narrow sense, and run on aviation specific OSI-based network-Aeronautical Telecommunication Network (ATN). This setting poses a major challenge at the institutional and engineering levels, but considering the current demand level for ATC-related data, this setting is controllable so far.

This situation will change as ATM moves to the field of big data. In addition to the traditional CPDLC services (such as TBO), the gradual introduction of new data link services, similar to streaming media, will put forward an unprecedented demand level for the capability and integrity of air-ground connection, as the operational concept favors automated functions where data plays a major role. Therefore, upgrading the ground broadband capability in protecting the aviation spectrum is proved to be a logical step for the future CSP network to meet the operational needs of both airlines and ANSP customers. LDACS provides a feasible means to meet this requirement, because it has some basic attributes, including protected aviation spectrum allocation, the ability to resist network security risks, the ability of local Internet Protocol (IP), and aviation standards under development.

In the future leap forward development, the multiple stakeholders mentioned above in the CSP chain need to work together to determine the transition road map. The road map should clearly state the business benefits and ANSP added value brought by new applications through the scalable and flexible ground broadband infrastructure, and can be used to supplement the emerging broadband satellite capabilities. This transition may start from local deployment, demonstrating the early operation of ATS/B2 and ATS/B3 applications (including TBO).

7. SUMMARY

This report analyzes the concept of 4DT-based operation and its typical scenarios, reviews the development process of LDACS, analyzes the advantages of LDACS compared with other data link technologies and the added value it brings to stakeholders and end users, and studies the architecture, functions, interfaces and other contents of LDACS. It provides theoretical support and input for the subsequent L-band broadband data communication architecture design for 4DT-based operation.