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Review of Current and Future ATM Communication Networks

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Abstract

This report reviews current and planned IP-based communication networks and protocols for the Aeronautical Telecommunication Network (ATN), focusing on mobility management in multilink environments. It aims to identify state-of-the-art mobility solutions, highlight their limitations, and guide the development of mobility scenarios for future testing and validation of the ATMACA solution. The report is based on a comprehensive literature review and is intended for researchers, industry professionals, and policymakers. It covers the evolution of the ATN to the Internet Protocol Suite (IPS), key communication technologies, mobility management protocols, and data link selection in multilink environments. The report also highlights related SESAR projects.

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ATMACA

AIR TRAFFIC MANAGEMENT AND COMMUNICATION OVER ATN/IPS

ATMACA

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List of Acronyms

Acronym	Name
ACARS	Aircraft Communications Addressing and Reporting System
ADS	Automatic Dependent Surveillance
ADS-B	Automatic Dependent Surveillance-Broadcast
ADS-C	Automatic Dependent Surveillance-Contract
AeroMACS	Aeronautical Mobile Airport Communication System
AIDC	Air Traffic Services Interfacility Data Communication
AIS	Aeronautical Information Services
ACL	ATC Clearances
ACM	ATC Communications Management
AMC	ATC Microphone Check
AMSS	Aeronautical Mobile Satellite Service
ANSP	Air Navigation Service Provider
AOC	Aeronautical Operational Control
ASBU	Aviation System Block Upgrades
ATC	Air Traffic Control
ATIS	Automatic Terminal Information Service
ATM	Air Traffic Management
ATMACA	Air Traffic Management and Communication over ATN/IPS
ATN	Aeronautical Telecommunication Network
ATN/IPS	Aeronautical Telecommunication Network/Internet Protocol Suite
ATN/OSI	Aeronautical Telecommunication Network/Open Systems Interconnection
ATS	Air Traffic Service
ATSP	Air Traffic Service Provider
CLNP	Connectionless-mode Network Protocol
CNS	Communication, Navigation, and Surveillance
CoA	Care-of-Address
CPDLC	Controller-Pilot Data Link Communications
DARP	Dynamic Airborne Reroute Procedure
DCL	Departure Clearance
D-FIS	Data Link Flight Information Services
DLIC	Data Link Initiation Capability
DLS	Data Link Service

D-TAXI	Data Link Taxi Clearance
D-VOLMET	Digital VOLMET
EIDs	Endpoint Identifiers
EUROCAE	European Organization for Civil Aviation Equipment
FA	Foreign Agent
FAA	Federal Aviation Administration
FANS	Future Air Navigation System
FDD	Frequency-Division Duplex
F-HMIPv6	Fast Handover for Hierarchical Mobile IPv6
FCI	Future Communication Infrastructure
FIS	Flight Information Service
FIS-B	Flight Information Service-Broadcast
FMIPv6	Fast handovers for MIPv6
FPL	Flight Plan
GANP	Global Air Navigation Plan
GB-LISP	Ground-based Locator/ID Separation Protocol
GEO	Geostationary Earth Orbit
GETVPN	Group Encrypted Transport VPN
HA	Home Agent
HF	High Frequency
HMIPv6	Hierarchical Mobile IPv6
HoA	Home Address
ICAO	International Civil Aviation Organization
IDRP	Inter-Domain Routing Protocol
IETF	Internet Engineering Task Force
IPS	Internet Protocol Suite
ISO	International Organization for Standardization
LDACS	L-Band Digital Aeronautical Communications System
LEO	Low Earth Orbit
LISP	Locator/ID Separation Protocol
MAKE	Mutual Authentication and Key Establishment
MIPv6	Mobile Internet Protocol Version 6
MN	Mobile Node
M-SNDCF	Mobile Sub-Network Dependent Convergence Function

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NEMO	Network Mobility
OCL	Oceanic Clearance
ORP	Oceanic, Remote, and Polar
OSI	Open Systems Interconnection
PDC	Pre-Departure Clearance
PMIPv6	Proxy Mobile IPv6
QoS	Quality of Service
RLOCs	Routing Locators
RPAS	Remotely Piloted Aircraft Systems
RTCA	Radio Technical Commission for Aeronautics
SARPs	Standards and Recommended Practices
SATCOM	Satellite Communications
SDN	Software Defined Networking
SESAR	Single European Sky ATM Research Programme
SIP	Session Initiation Protocol
SSR	Secondary Surveillance Radar
TBO	Trajectory-Based Operations
TIS-B	Traffic Information Service-Broadcast
TP4	Transport Protocol class 4
UAS	Unmanned Aircraft System
ULCS	Upper Layer Communications Service
URI	Uniform Resource Identifier
VDL	VHF Data Link
VDLm2	VHF Data Link Mode 2
VHF	Very High Frequency
VoIP	Voice over Internet Protocol
VPN	Virtual Private Network
WXXM	Weather Information Exchange Model

1 Introduction

1.1 Purpose and scope

The aim of this report is to present and review current and planned Aeronautical Telecommunication Network (ATN) IP-based communication networks and protocols that support aeronautical applications and services. The focus is on mobility management, particularly in a multilink environment. A multilink environment enables aircraft to connect to multiple data links (e.g., satellite, terrestrial radio, cellular) simultaneously or sequentially. Mobility in the ATN presents a challenge: maintaining continuous communication between ground-based systems and airborne avionics while exchanging data across different communication paths. The ATN must ensure that data can be transmitted without interruption, regardless of changes in the aircraft's location, network coverage, or the available data links. While maintaining connectivity across multiple data links is a key objective, mobility management in the ATN must also handle user mobility, session mobility, and service mobility, each of which is critical for supporting modern aeronautical operations. User mobility allows a single user to maintain a consistent identity and access personalized services across different devices. Session mobility ensures active communication sessions remain uninterrupted during network or device transitions. Service mobility enables seamless access to the same services and applications across different networks and devices, maintaining service quality despite changes in connectivity.

The insights gathered in this report will pave the way for identifying state-of-the-art mobility solutions and their limitations. The findings will also aid in the creation of mobility scenarios and use cases, which will be developed in task T2.3 of the ATMACA project. These scenarios and use cases will be used in T3.3 to test, assess, and validate the ATMACA IP-based communication protocol, which will be designed in T3.1 and implemented in T3.2. They will also be used to develop green route operations, aeronautical applications, and human-machine interface to be validated in T6.4.

In addition to researchers in the areas of networking and aeronautical communications, this report is intended for industrial organizations, regulatory authorities, and policymakers.

1.2 Methodology

This literature research is based on the identification, selection, analysis, and synthesis of relevant materials. The research was conducted using academic databases (Google Scholar, IEEE Xplore, ACM Digital Library), SESAR and EU-funded project databases, institutional repositories for theses and dissertations, as well as websites. This review is an extension of the survey paper [OzHaCh24] by the same authors.

1.3 Structure of the document

The report is organized as follows. Section 2 introduces the ATN, describing its evolution from Open Systems Interconnection (OSI) to Internet Protocol Suite (IPS). Section 3 presents the main aeronautical communication data link technologies. It also presents the Future Communication Infrastructure (FCI), a new IP-based system designed under the SESAR scope to support ATN/IPS multilink capability and ensure seamless mobility between different data link systems to improve efficiency, capacity, safety, and reduce environmental impact. Section 4 provides an overview of aeronautical data link applications and services. Section 5 presents and analyses mobility management protocols and their use in Air Traffic Management (ATM), highlighting their importance for ensuring session continuity as aircraft move between different access networks. Section 6 reviews data link selection in a multilink environment, where multiple access networks are available simultaneously. Section 7 highlights limitations of the current mobility solutions and discusses open problems and challenges. Section 8 presents the conclusions. Finally, Appendix A lists and briefly describes related SESAR projects.

2 Aeronautical Telecommunication Network (ATN)

The ATN is a global aviation standard telecommunication network designed to provide seamless ground-to-ground and air-to-ground communications services to various safety and non-safety purposes over different air-ground subnetworks. The ATN consists of:

- ATN internetwork, which consists of intermediate systems (routers), end systems (computers), and communication links.
- ATN subnetworks, which are independent communication networks (such as VHF Data Link (VDL), SATCOM, etc.) that serve as the physical transport layer for transferring information between ATN systems. These subnetworks provide essential connectivity for air-to-ground and ground-to-ground communications.
- ATN applications. These are the specific services built on top of the ATN infrastructure. They include Context Management (CM), Automatic Dependent Surveillance (ADS), Controller- Pilot Data Link Communications (CPDLC), and Data Link Flight Information Services (D-FIS).

Historically, the ATN was primarily based on the Open Systems Interconnection (OSI) model. However, with the increasing maturity and widespread adoption of Internet Protocol (IP) technologies, the ATN is evolving to incorporate the Internet Protocol Suite (IPS) model [JSMP16]. Although the International Civil Aviation Organization (ICAO) standardized ATN/OSI, its deployment was limited. The next-generation ATN, based on ATN/IPS, aims to provide secure and continuous communication services for aeronautical applications across different operational environments.

The original decision to use OSI protocols for the ATN was primarily policy driven. However, since the ATN's initial specification, IP protocols have emerged as the de facto standard for open communication and network interconnection due to their widespread availability, lower cost, and inherent advantages in interoperability and scalability. Therefore, validating IP for aeronautical communication is a key objective of ongoing research. This research suggests that the next-generation ATN will primarily operate over IP, with legacy systems potentially continuing to use OSI protocols during a transition period [OzHaCh24]. Table 1 compares the features and capabilities of ATN/OSI and ATN/IPS.

Features and Capabilities	ATN/OSI	ATN/IPS (IPv6)
Air-to-Ground Architecture	Functionally Equivalent	Functionally Equivalent
Ground-to-Ground Architecture	Full stack more complex	Same as Air-to-Ground Architecture protocol stack
Mobility Support	Limited support	Full support
Quality of Service	Limited services and priorities	Real-time protocols, DiffServ
Security	Security label, limited capability	More capability, IPsec, Public Key Infrastructure (PKI) available
Multicasting	No support	Supported
Network Management	Common Management Information Protocol (CMIP) – more complex	Simple Network Management Protocol (SNMP) – simple and widely deployed

Table 1: ATN/OSI and ATN/IPS Architectural Comparison (based on [OzHaCh24])

2.1 ATN/OSI

The ATN/OSI stack includes the Upper Layer Communications Service (ULCS), which provides a logical interface to applications through the Dialogue Service. The primary function of ULCS is to manage communication sessions between airborne and ground systems. ULCS contains streamlined versions of the OSI Presentation and Session Layers.

ULCS operates on top of the OSI-defined Transport Protocol Class 4 (TP4), which provides reliable, connection-oriented transport services. Below TP4, the OSI Network Layer uses the Connectionless Network Protocol (CLNP) for routing and data transfer.

In the air-ground environment, CLNP works over the Mobile Sub-Network Dependent Convergence Function (M-SNDCF), which adapts the network layer to different mobile subnetworks. M-SNDCF runs over VHF Data Link Mode 2 (VDLm2), a key protocol for digital data exchange in air-ground communications over VHF frequencies.

The ATN standards are based on the OSI protocol suite rather than the Internet Engineering Task Force (IETF) suite, often referred to as the TCP/IP protocols. This choice was made because the OSI protocols were more formally specified, included detailed protocol implementation conformance matrices, and used profiles that combine specific functions at each protocol level, making them more suitable for aviation certification.

The ATN/OSI recognizes a limited set of subnetworks, including SSR Mode Select (Mode S), VDLm2, Aeronautical Mobile Satellite Service (AMSS), Gatelink, and High Frequency (HF) communications [McPa24].

To support mobility and ensure seamless routing across different network domains, ATN/OSI uses the Inter-Domain Routing Protocol (IDRP) for inter-domain routing and CLNP for forwarding data packets. This combination allows for efficient routing as aircraft move between different network domains.

2.2 ATN/IPS

The ATN/IPS protocol stack is specified in ICAO Doc 9896 [ICAO9896], which defines the standards for using IP-based communication in the ATN.

The ATN/IPS stack includes the IP Dialogue Service, which presents the same logical interface to legacy ATN applications as the Dialogue Service did in the OSI-based ATN stack. The IP Dialogue Service provides the ULCS Dialogue Service primitives and transfers the necessary parameters between peer applications. The IP Dialogue Service operates over the IETF TCP or UDP transport protocols, which in turn, run over the IP protocol at the network layer. In the air-ground environment, IP uses the IETF Mobile IP protocol.

The manual for ATN using IPS standards and protocols [ICAO9896] outlines the communication protocols required to enable the transition to an ATN based on the TCP/IP model. The manual specifies a core set of IETF protocols for both ground-to-ground and air-to-ground communications, with a focus on introducing IPv6. A key reason for introducing IPv6 is its ability to support a much larger address space and more advanced networking capabilities than IPv4. As the number of aircraft, ground stations, and mobile nodes connected to the ATN continues to grow, a scalable addressing solution is essential. Unlike IPv4 with its 32-bit address system, IPv6 has a 128-bit address system that offers an

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almost unlimited number of addresses. Furthermore, IPv6 simplifies network configuration and enhances security and mobility features, which are crucial for ensuring seamless and reliable connectivity for airborne and ground-based systems.

The ATN/IPS network architecture requires compatibility with the following protocols [ICAO9896]: IPv6 [HiDe06], IPv6 Addressing Architecture, Internet Control Message Protocol version 6 (ICMPv6) [CoDeGu06], and Mobile IPv6 (MIPv6) [DeHi98], initially without route optimization. Additionally, the manual allows for the extension of MIPv6 to support network mobility. MIPv6 provides mobility management at the network layer, allowing a mobile node (e.g., an aircraft) to maintain connectivity and remain reachable via a static address called Home Address (HoA), regardless of its current network address, known as the Care-of Address (CoA).

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3 Aeronautical Communication Data Link Technologies

The term data link in the context of aviation typically refers to communication technologies that enable reliable digital communication between aircraft and ground systems. These data link technologies support the exchange of messages such as Air Traffic Control (ATC) communications and facilitate communication for flight information services, advisory services, and alerting.

3.1 VHF Data Link mode 2 (VDLm2)

VHF Data Link (VDL) enables text-based messaging between flight crews and air traffic controllers. VDL supports critical ATS applications such as CPDLC and D-FIS. VDL specifies aspects of OSI Layers 1 (Physical) and 2 (Data Link). There are four variants of VDL: mode 1 was an early analog version; mode 3 was an attempt to integrate digital voice capabilities but failed to gain adoption by airlines; mode 4 was initially intended for Automatic Dependent Surveillance-Broadcast (ADS-B) but was overtaken by mode S in 2003 for data link services; VDLm2 is designed to support higher-throughput communications. VDLm2 is the only VDL mode still in active use. It supports the ATN (Figure 1) and provides a reliable data link for messaging services. However, as aircraft move within ATC sectors, connections may need to be re-established due to handovers between VHF ground stations. Mobility management in VDLm2 faces several structural, technical, and operational challenges [BGLP14].

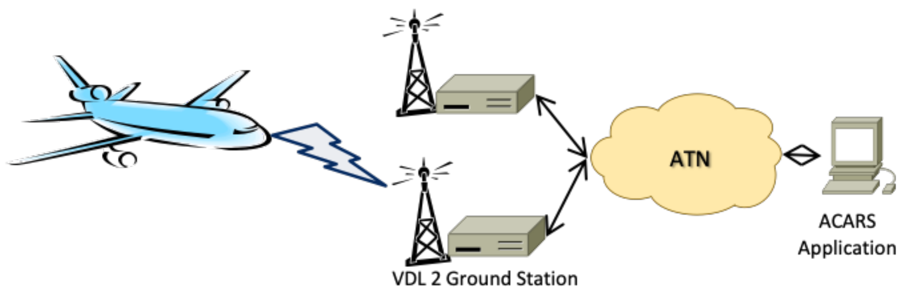

Figure 1: VDLm2 (based on [OzHaCh24])

3.2 Aeronautical Mobile Airport Communication System (AeroMACS)

AeroMACS operates near airports and has been proposed as an air-to-ground data link communication technology to reduce congestion in VHF voice channels during airport ground operations. AeroMACS is based on IEEE 802.16 (WiMAX) technology and offers data rates of up to 7.2 Mbps in both directions [MEGM23]. It has been deployed in over 40 airports [MEGM23]. Kerczewski et al. [KeApDi13] conclude that AeroMACS can support safety-critical aviation communications for both fixed and mobile applications. However, tests reported in [LiZhHe19] indicate that the system's transmission quality is reduced under non-line-of-sight (NLOS) conditions. The system can provide 1 Mbps of communication capacity under mobility conditions and can also operate effectively in heavy rainfall.

3.3 L-Band Digital Aeronautical Communications System (LDACS)

The LDACS is an integrated Communication, Navigation, and Surveillance (CNS) system. It serves as an access technology for the ATN/IPS. LDACS supports current ATS, Aeronautical Operational Control (AOC) data, digital voice, and is designed to accommodate future applications such as 4D trajectories [Mäur22b]. LDACS is a terrestrial-based cellular system that uses a frequency-division duplex (FDD) scheme, with two 495.05 kHz channels: one for the forward link handling ground-to-air communications, and one for the return link managing air-to-ground communications [Hain24]. Each LDACS cell can support up to 512 aircraft stations, with user-data rates ranging from 230 to 1428 kbps in the forward link and from 235 to 1390 kbps in the return link. This offers up to 90 times the net capacity of VDLm2 [Mäur22b].

Validation efforts within the SESAR and Horizon 2020 programmes demonstrated that LDACS meets the expected ATN performance requirements [RSMG19], [Hain24]. Flight trials [Bell22] confirmed that LDACS provides the high data throughput required for modern aeronautical applications.

The paper [Mäur22b] proposes a secure ground handover between LDACS cells using the Mutual Authentication and Key Establishment (MAKE) procedure.

LDACS is currently being standardized by ICAO and the IETF [MaGrSc23]. SESAR [MaGrSc23] has proposed LDACS as the successor to VDLm2 for European ATM communications.

3.4 Satellite Communication (SATCOM)

SATCOM refers to data transmission via satellites in various orbits and at different distances from Earth. SATCOM has been instrumental in overcoming communication challenges in Oceanic, Remote, and Polar (ORP) regions, as well as the Asia-Pacific, where vast distances and remote locations make terrestrial data links impractical. To support ATM in these areas, the ICAO Aeronautical Mobile-Satellite (Route) Service (AMS(R)S) Standards and Recommended Practices (SARPs) define three classes of satellite communication links: Class C for procedural control and less demanding ATM functions in ORP regions, Class B for trajectory-based operations, and Class A for future performance-based operations. This tiered approach to SATCOM ensures scalable solutions as ATM requirements evolve [Mäur22a].

Inmarsat, introduced in 1979 for maritime applications, has since evolved to provide advanced aeronautical communication services. The Inmarsat aeronautical network is compliant with ICAO SARPs and Radio Technical Commission for Aeronautics (RTCA) DO-262D, offering two-way voice and data services for both ATC and AOC at various data rates. Inmarsat's early Aero-H service provided 10.5 kbps in the global beam, later upgraded to Aero-H+ and Aero-HSD+ for improved performance (64 kbps). The Inmarsat Iris system, a certified Class B system based on SwiftBroadband technology, offers speeds of up to 432 kbps, although it faces challenges with IPv6-based ATN/IPS integration. The latest JX system provides enhanced QoS, with data rates of up to 50 Mbps in the forward link and 5 Mbps in the reverse link, ensuring secure end-to-end connections and robust data integrity [Mäur22a].

Iridium, founded in 1991, initially provided aeronautical services at communication speeds between 600 and 2400 bps. The Iridium NEXT second-generation satellites, operating in the L-band, have significantly upgraded services, offering 22–88 kbps in the midband and 128–704 kbps in broadband. Iridium's key aeronautical service, Iridium Certus, is a Class B system (with the potential to evolve to

Class A). Certus offers IPv4 services but faces similar challenges as Inmarsat with IPv6 integration [Mäur22a].

Low Earth Orbit (LEO) SATCOM for aeronautical communication is provided by SpaceX's Starlink, with over 8,000 satellites, and Eutelsat's OneWeb, with more than 630 satellites. Due to their closer proximity to Earth compared to Geostationary Earth Orbit (GEO) satellites, LEO systems offer lower latency. Starlink provides download speeds ranging from 40 to 220 Mbps per aircraft, with latencies under 99 ms [STAR24]. OneWeb offers speeds up to 195 Mbps and low-latency connectivity to aircraft [One24]. Another LEO system under development is Telesat's Lightspeed, which aims to deploy 198 satellites to provide LEO IP SATCOM for aeronautical communication [Tele24].

3.5 Future Communication Infrastructure (FCI)

The FCI is an IPS-based communication framework designed to ensure reliable aeronautical communication by integrating multiple subnetworks. FCI is a key component of the SESAR program [SESAR20]. FCI's air-ground data link services can use various technologies to meet end-to-end communication requirements for future ATM.

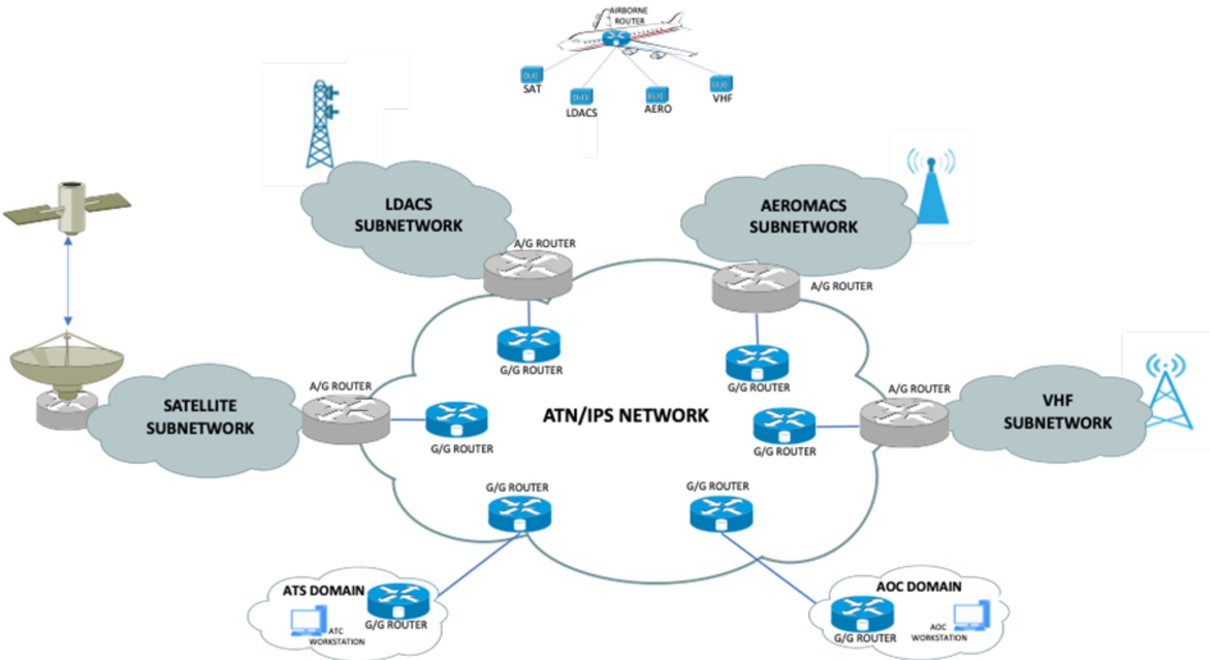

Figure 2: ATN/IPS Network Architecture (based on [OzHaCh24])

FCI aims to integrate legacy narrowband technologies such as VDLm2, alongside newer IP-based solutions (Figure 2).

Various data link communication technologies can coexist and be used based on network availability and operational needs. Short-range communication systems, like AeroMACS, are designed for high-data-rate communication near airports. For continental communications, line-of-sight systems such as VDLm2 and LDACS can be used. For oceanic and remote continental regions, SATCOM can offer a critical beyond-line-of-sight communication solution. It is typically used where ground-based infrastructure is unavailable, providing continuous connectivity despite its higher operational costs and latency compared to terrestrial systems.

The FCI solution developed in SESAR PJ14-W2-77 integrates LDACS, SATCOM, VDLm2 and AeroMACS. It supports ATN/IPS multilink capability and aircraft mobility between the different data link systems [SESAR23].

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4 Data Link Applications and Services in Aeronautical Communication

In aeronautical communication, particularly in ATM, data link applications and data link services are fundamental concepts that enable the exchange of digital messages between aircraft and ground systems, as well as among aircraft themselves. These applications and services enhance situational awareness, reduce pilot and air traffic controller workload, and improve the overall safety and efficiency of air transportation. This section explores the various data link applications and services used in aeronautical communications, the technologies and protocols that underpin them, and their status and future trends shaping the evolution of aviation communication systems.

A data link application is the implementation of data link technology to achieve specific ATM operational functionalities [ICAO9694]. Data link applications are software functions or protocols that define how data is formatted, processed, and managed for specific communication purposes in aeronautical systems. They specify the message sets, procedures, and operational rules for exchanging information between communication parties (e.g., pilots and air traffic controllers). Examples include CPDLC and Automatic Dependent Surveillance-Contract (ADS-C).

A service is a set of ATM-related transactions, both system supported and manual, within a data link application, which have a clearly defined operational goal. Each data link service is a description of its recommended use from an operational point of view [ICAO9694]. Data link services are the operational capabilities provided to users (e.g., pilots, controllers) through the implementation of data link applications. They represent the functionalities or features that enable specific communication tasks. They focus on what is provided to the user, such as the ability to send and receive specific types of messages or perform certain communication functions. For example, CPDLC Service enables text-based communication between pilots and controllers. Regarding ADS-C Reporting Service, it allows automatic reporting of aircraft position and intent data.

Data link applications and data link services are closely related. Applications define the technical protocols and procedures, while services refer to the operational use of these applications by end-users. Data Link Applications are the enablers that implement the technical capabilities. Data Link Services are the functional outcomes or user-facing features provided by these applications.

4.1 Overview of Key Data Link Applications and Services

The field of aeronautical communications is continually evolving, with new applications and services developed to meet the growing demands of air traffic management. The data link applications and services listed below are developed or standardized by international aviation organizations such as ICAO, RTCA, Federal Aviation Administration (FAA), SESAR Joint Undertaking, and the European Organization for Civil Aviation Equipment (EUROCAE). The following sections provide a comprehensive review of 19 key data link applications and services used in ATM. Here, data link applications and data link services are used interchangeably.

- Controller-Pilot Data Link Communications (CPDLC)
- Automatic Dependent Surveillance-Contract (ADS-C)
- Context Management (CM)
- Data Link Initiation Capability (DLIC)

- Departure Clearance (DCL)
- Digital-Automatic Terminal Information Service (D-ATIS)
- Digital VOLMET (D-VOLMET)
- Oceanic Clearance (OCL)
- Data Link Flight Information Services (D-FIS)
- Air Traffic Services Interfacility Data Communication (AIDC)
- Traffic Information Service-Broadcast (TIS-B)
- Flight Information Service-Broadcast (FIS-B)
- Automatic Dependent Surveillance-Broadcast (ADS-B)
- Pre-Departure Clearance (PDC)
- Data Link Taxi Clearance (D-TAXI)
- Aeronautical Information Services (AIS)
- Flight Plan Uplink (FPL Uplink)
- Dynamic Airborne Reroute Procedure (DARP)
- Digital Automatic Terminal Information Service Broadcast (D-ATIS-B)

Table 2 summarizes these 19 key data link applications and services used in air traffic management, detailing their descriptions and main functions.

Application	Description	Main Functions
1. CPDLC	Enables text-based communication between pilots and air traffic controllers, supplementing or replacing voice communications. Air/Ground Trajectory Synchronization through lateral and vertical CPDLC clearances supports the implementation of Trajectory-Based Operations (TBO).	- Facilitates clear and efficient communication between pilots and ATC. - Reduces voice communication load. - Provides standardized message formats.
2. ADS-C	Allows aircraft to automatically send position reports and other surveillance data to ATC under predefined contracts. ADS-C is the primary data link application for 4D trajectory data sharing.	- Provides automatic position and intent reporting. - Enhances surveillance in non-radar areas. - Supports ATC in monitoring and separation.
3. CM	Manages the data link communication context between an aircraft and ground systems.	- Establishes and maintains data link sessions. - Handles aircraft identification and addressing. - Supports initiation of data link applications like CPDLC.
4. DLIC	Part of the Context Management application; establishes the data link communication context.	- Enables initial logon between aircraft and ground systems. - Sets up data link communication parameters. - Prerequisite for other data link services.
5. DCL	Provides pre-departure clearances from ATC to the flight deck via data link.	- Delivers departure clearances electronically. - Reduces voice communication.

		- Speeds up the clearance delivery process.
6. D-ATIS	Delivers automated terminal information service messages, including weather and airport operational data, to aircraft via data link.	- Provides up-to-date terminal information. - Reduces the need for pilots to listen to voice ATIS broadcasts. - Improves situational awareness.
7. D-VOLMET	Supplies en-route meteorological information to aircraft via data link.	- Provides continuous weather updates. - Enhances flight safety by informing pilots of en-route weather conditions. - Reduces workload by automating weather data reception.
8. OCL	Enables aircraft to receive oceanic route clearances from ATC via data link.	- Delivers oceanic clearances electronically. - Improves efficiency in oceanic airspace. - Reduces communication errors and delays.
9. D-FIS	Provides pilots with essential flight information such as weather updates, NOTAMs, and other advisories via data link.	- Supplies critical flight information. - Supports informed decision-making. - Enhances safety and efficiency.
10. AIDC	Automates the exchange of flight data between ATC units.	- Facilitates coordination between ATC units. - Reduces voice communication. - Enhances efficiency and accuracy in flight data transfer.
11. TIS-B	Provides aircraft with information about other nearby aircraft, including those not equipped with ADS-B Out.	- Enhances situational awareness. - Aids in collision avoidance. - Supplements ADS-B data for a comprehensive traffic picture.
12. FIS-B	Broadcasts flight information such as weather data, turbulence reports, and other pertinent information to aircraft.	- Provides continuous broadcast of flight information. - Improves pilot awareness. - Reduces the need for voice requests and manual data retrieval.
13. ADS-B	Allows aircraft to broadcast their position and other data to ground stations and to other aircraft.	- Provides real-time position data. - Enhances surveillance and traffic management. - Supports collision avoidance systems.
14. PDC	Provides departure clearances to pilots via data link, often coordinated with airline operations centres.	- Streamlines the clearance delivery process. - Reduces voice communication and potential misunderstandings. - Improves efficiency at busy airports.
15. D-TAXI	Allows taxi clearances to be sent from ATC to the flight deck via data link. Sesar project D-Taxi has validated the exchange of non-time critical messages between ATC and	- Delivers taxi instructions electronically. - Reduces miscommunications on the ground. - Improves ground movement efficiency and safety.

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	Mobiles: Contact, Monitor, Expected Taxi Route, Start Up, Push back, Taxi-In, Taxi-Out and Taxi Revision	
16. AIS	Provides aeronautical information such as NOTAMs, charts, and procedural updates via data link.	- Supplies essential navigational information. - Ensures pilots have current data. - Supports compliance with regulatory procedures.
17. FPL Uplink	Enables the airline operations center to send updated flight plans directly to the aircraft via data link.	- Updates flight plans in real-time. - Reduces manual data entry errors. - Enhances operational flexibility and responsiveness.
18. DARP	Allows aircraft to request and receive route changes during flight over oceanic and remote areas via data link.	- Facilitates in-flight rerouting for optimal efficiency. - Optimizes fuel consumption and time management. - Responds to changing weather or traffic conditions.
19. D-ATIS-B	An extension of D-ATIS that broadcasts terminal information to multiple aircraft simultaneously via data link.	- Provides continuous terminal information updates. - Improves situational awareness. - Reduces frequency congestion and the need for voice communications.

Table 2: Summary of Key Data Link Applications and Services

There are many other data link applications and services beyond those listed above. These applications span a wide range of functions, including enhanced communication, improved situational awareness, operational efficiency, safety enhancements, and integration of new types of aircraft into the airspace system. The following applications and services are some examples to provide specific functionalities via data link:

- Data Link Graphical Weather Services: Transmits graphical weather data directly to the cockpit displays via data link.
- Clearance and Information for Synthetic Vision (CLIS): Provides clearances and traffic information formatted for display on synthetic vision systems via data link.
- Time of Arrival Control via Data Link: Enables aircraft to receive time-based metering instructions from ATC via data link.
- Surface Movement Guidance via Data Link: Provides taxi routing and clearances to aircraft via data link for surface movement.
- Weather Information Exchange Model (WXXM) via Data Link: Transmits standardized weather information using WXXM formats via data link.
- Unmanned Aircraft System (UAS): Specialised data link applications for communication with unmanned aircraft systems.
- Remote Piloted Aircraft Systems (RPAS): Data link services specific to remotely piloted aircraft operating in controlled airspace.

As technology advances and the demands on the global air traffic system increase, it can be expected that the development and implementation of additional data link applications and services will be needed to support the evolving needs of aviation.

4.2 Standardized Data Link Services

The ICAO has standardized several Data Link Services (DLS) as part of its global strategy to enhance air traffic management through digital communications, supported by regional initiatives like the European SES framework and FAA implementations. These services are integral to CPDLC and fall under the guidance of ICAO Annex 10 and operational documents like the Global Operational Data Link Document (GOLD)[ICAO10037]. DLS are mandated in Europe with EC Regulation (EU 29/2009), referred to as the DLS Implementing Rule (DLS IR). The DLS IR, following various amendments of the initial regulation, has been in force since February 2020. The DLS IR requires the air navigation service providers (ANSPs) to offer four DLS and the airspace operators to be capable (i.e. to have equipped aircraft and trained crews) to operate these services over ATN VDLm2 for all flights in the European airspace operating above FL285. The standardized DLS within CPDLC framework include:

- DLIC (Data Link Initiation Capability)
- ACL (ATC Clearances)
- ACM (ATC Communications Management)
- AMC (ATC Microphone Check)

1. Data Link Initiation Capability (DLIC)

DLIC establishes the initial data link connection between an aircraft and ground ATC systems. It is the foundational service that enables subsequent CPDLC communications.

Functionality:

- Aircraft Logon: The aircraft sends a logon request to the ATC facility using its unique identification, such as the aircraft registration or flight number.
- Connection Establishment: Upon receiving the logon request, the ground system verifies the information and establishes a CPDLC connection with the aircraft.
- Capability Exchange: Both the aircraft and the ground systems exchange information about their data link capabilities to ensure compatibility.

DLIC must be successfully established before other CPDLC services like ACL, ACM, and AMC can be used. DLIC ensures that communications are exchanged with the correct aircraft, enhancing security and reducing miscommunication risks.

2. ATC Clearances (ACL)

ACL is used for sending and receiving ATC clearances, instructions, and advisories via data link. This includes messages related to altitude changes, route modifications, speed adjustments, and other flight parameters.

Functionality:

- Digital Clearances: ATC can send clearances in a standardized, text-based format, which the pilot can read, review, and acknowledge.
- Acknowledgment Protocol: Pilots must acknowledge receipt and acceptance (or inability to comply) of the clearance, ensuring mutual understanding.
- Message Storage: Both pilots and controllers have a record of the clearance messages, which can be referred to at any time.

ACL allows pilots to read and respond to messages when workload permits, enhancing cockpit efficiency.

3. ATC Communications Management (ACM)

ACM manages the transfer of communication responsibility between different ATC sectors or controllers as the aircraft progresses along its flight path.

Functionality:

- Transfer of Control: ATC sends messages instructing the pilot to contact a new controller or switch to a different frequency.
- Seamless Transition: Facilitates smooth handovers between controllers without the need for voice communication.
- Frequency Information: Provides precise frequency details and contact information for the next ATC unit.

ACM reduces the need for voice communication during sector handovers, saving time and reducing frequency congestion. ACM ensures pilots have accurate information for contacting the next controller, minimizing the risk of communication gaps.

4. ATC Microphone Check (AMC)

AMC allows pilots and controllers to verify the status of voice communication equipment, ensuring that voice communication channels are functioning properly.

Functionality:

- Equipment Verification: Either the pilot or controller can initiate a microphone check to confirm that voice communications are operational.
- Problem Resolution: Helps identify and promptly address issues with voice communication systems.
- Backup Communication: Ensures that voice channels are available as a backup to data link communications.

ACM is used before departure to confirm communication equipment is working correctly. ACM is used if there is a suspicion of communication issues during flight operations.

The CPDLC standardized data link services - DLIC, ACL, ACM, and AMC - are essential components of modern aviation communication systems. They work together to provide a robust framework that enhances efficiency, safety, and reliability in interactions between aircraft and ATC.

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- DLIC establishes the necessary groundwork for all subsequent data link communications.
- ACL allows for precise and efficient exchange of critical flight instructions.
- ACM ensures that communication remains seamless as control responsibility shifts between ATC units.
- AMC provides a means to verify and maintain the integrity of communication systems throughout the flight.

Aviation authorities and industry groups are continually working on expanding and standardizing data link applications and services to further improve operational efficiency and safety. Future developments may see applications and services becoming more standardized or integrated into broader communication systems. Since DLIC is foundational to enable other DLS (like ACL, ACM, and AMC) to function, we will discuss DLIC and CPDLC (ACL, ACM, AMC) separately in the following sections.

4.3 Classification of Data Link Applications and Services

Classification of data link applications and services can be approached from several perspectives, including their functional roles, the services they provide, and the communication domains they operate within. Below is a detailed classification of key data link applications and services in ATM communication networks.

4.3.1 Classification by Functional Roles

1. Controller-Pilot Communication

These applications and services enhance communication between pilots and air traffic controllers, supplementing or replacing traditional voice communications.

- CPDLC, DCL, PDC, D-TAXI, OCL

Relationships and Description:

- CPDLC is the core application enabling text-based communication between pilots and controllers.
- DCL and PDC are specific implementations of CPDLC for delivering pre-departure clearances.
- D-TAXI: Navigating the aircraft to the runway.
- DCL and D-Taxi are specialized applications that enhance ground operations.
- OCL provides oceanic route clearances, crucial for flights over oceanic and remote areas.

Interrelationships:

- CPDLC serves as the foundational technology for DCL, PDC, D-TAXI, and OCL.
- DCL, PDC, D-TAXI, and OCL use standardized message formats and protocols defined by CPDLC.

2. Surveillance and Traffic Management

These applications and services improve situational awareness and traffic management through automatic position reporting and traffic information dissemination.

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- ADS-C, ADS-B, TIS-B

Relationships and Description:

- ADS-C allows aircraft to send position reports under predefined contracts, enhancing surveillance in non-radar areas.
- ADS-B enables aircraft to broadcast their position and receive data from other aircraft and ground stations.
- TIS-B provides traffic information about nearby aircraft, including those without ADS-B Out capability.

Interrelationships:

- ADS-B and TIS-B work together to provide comprehensive traffic information.
- ADS-C complements ADS-B in areas without adequate ADS-B coverage.

3. Context Management

These applications and services manage the initiation and maintenance of data link communication sessions between aircraft and ground systems.

- CM, DLIC

Relationships and Description:

- CM handles the overall management of data link sessions, including logon and address resolution.
- DLIC is a component of CM, specifically responsible for initiating the data link communication context.

Interrelationships:

- DLIC is the first step in establishing a data link session managed by CM.
- CM is essential for the operation of other data link applications and services like CPDLC and ADS-C.

4. Information Services

These applications and services provide pilots with essential flight, weather, and aeronautical information via data link.

- D-FIS, FIS-B, D-ATIS, D-ATIS-B, D-VOLMET, AIS

Relationships and Description:

- D-FIS offers essential flight information such as weather updates and NOTAMs and allows the automatic provision of data such as D-ATIS messages, meteorological reports.
- FIS-B broadcasts flight information continuously to equipped aircraft.

- D-ATIS and D-ATIS-B provide automated terminal information, with D-ATIS-B broadcasting to multiple aircraft simultaneously.
- D-VOLMET supplies en-route meteorological information.
- AIS delivers aeronautical information such as charts and procedural updates.

Interrelationships:

- D-FIS and FIS-B are complementary, with FIS-B providing broadcast services for the information available through FIS.
- D-ATIS, D-ATIS-B, and D-VOLMET specialize in delivering specific types of information (terminal and meteorological).
- AIS supports D-FIS by providing detailed aeronautical data.

5. Flight Planning and Dynamic Routing

These applications and services facilitate efficient flight planning and allow for dynamic changes during flight.

- FPL Uplink, DARP

Relationships and Description:

- FPL Uplink enables airline operations centres to send updated flight plans directly to the aircraft.
- DARP allows aircraft to request and receive route changes via data link, optimizing for weather and traffic conditions.

Interrelationships:

- FPL Uplink supports DARP by enabling the transmission of updated flight plans resulting from reroute procedures.
- Both applications enhance flight efficiency and flexibility.
- DARP relies on accurate surveillance data from ADS-C and ADS-B to facilitate dynamic rerouting.

6. Ground-Ground Communications

Enhance coordination and data exchange between ground facilities.

- AIDC

Relationships and Description:

- AIDC automates the exchange of flight data between ATC units, reducing the need for voice coordination.

Interrelationships:

- While not directly involving aircraft, AIDC supports seamless ATM by ensuring controllers have up-to-date flight information.

Table 3 classifies the 19 key data link applications and services into 6 categories based on their main functions.

Category	Applications and Services
Controller-Pilot Communication	CPDLC, DCL, PDC, D-TAXI, OCL
Surveillance and Traffic Management	ADS-C, ADS-B, TIS-B
Context Management	CM, DLIC
Information Services	D-ATIS, D-VOLMET, D-FIS, FIS-B, AIS, D-ATIS-B
Flight Planning and Dynamic Routing	FPL Uplink, DARP
Ground-Ground Communication	AIDC

Table 3: Classification by Functional Roles

4.3.2 Categories of Communication, Navigation, and Surveillance systems

The following classification organizes the provided 19 Data Link Applications and Services into the categories of CNS systems. Some of them may fall into more than one category due to their multifunctional nature. Table 4 highlights the multifaceted roles of data link applications and services. While many of them primarily serve communication functions, several also play critical roles in navigation and surveillance.

1. Communication Systems

- Most of the applications fall under this category as they involve the exchange of information between various parties.
- Applications like CPDLC, DCL, PDC, D-TAXI, and OCL are directly involved in communicating clearances and instructions.

2. Navigation Systems

- Applications that provide data affecting the aircraft's routing and flight path are classified here.
- DARP, FPL Uplink, OCL, and D-TAXI directly influence navigation decisions.

3. Surveillance Systems

- ADS-C, ADS-B, and TIS-B are core surveillance applications that provide real-time position and movement data of aircraft.
- They enhance situational awareness and safety by allowing tracking of aircraft movement

Applications and Services	Communication	Navigation	Surveillance
1. CPDLC	✅		
2. ADS-C			✅
3. CM	✅		
4. DLIC	✅		
5. DCL	✅		

6. D-ATIS	✅		
7. D-VOLMET	✅		
8. OCL	✅	✅	
9. FIS	✅		
10. AIDC	✅		
11. TIS-B			✅
12. FIS-B	✅		
13. ADS-B			✅
14. PDC	✅		
15. D-TAXI	✅	✅	
16. AIS	✅		
17. FPL Uplink	✅	✅	
18. DARP	✅	✅	
19. D-ATIS-B	✅		

Table 4: Classification by Communication, Navigation, and Surveillance systems

4.3.3 Classification by Operational Domains

Table 5 summarizes the classification of data link applications and services according to the different phases of flight along with their primary functions.

Flight Phase	**Applications**	**Functions**
Pre-Flight and Departure	DLIC, DCL, PDC, D-TAXI, D-ATIS, D-ATIS-B, FPL Uplink, AIS, CM, CPDLC	- Establish communication. - Receive clearances. - Obtain necessary information.
En-Route Operations	CPDLC, ADS-C, D-VOLMET, D-FIS, FIS-B, TIS-B, ADS-B, AIS, CM, AIDC	- Maintain communication. - Receive updates. - Enhance situational awareness.
Oceanic and Remote Airspace	ADS-C, OCL, DARP, CPDLC, CM, DLIC, D-VOLMET, D-FIS, AIDC	- Ensure communication where traditional methods are limited.
Arrival and Approach	D-ATIS, D-ATIS-B, D-TAXI, AIS, TIS-B, ADS-B, CPDLC, CM	- Receive terminal information. - Manage descent and landing procedures.

Table 5: Classification by Flight Phases

4.4 ATN Standardized Air/Ground Applications

The ATN provides a global framework for standardized digital communication between aircraft and ground systems in ATM. ICAO has standardized four ATN air/ground applications (See the first four categories in Table 3) as: CM, ADS-C, CPDLC, and D-FIS [ICAO9896] [ICAO4444] [ICAO9705] [ICAO9880].

Table 6 summarizes four Standardized ATN Air/Ground Applications.

Application	Description	Standardization
1. CM	Manages data link communication contexts between aircraft and ground systems, including the DLIC.	ICAO Doc 9705, Doc 9880 (ATN/OSI protocols)
2. CPDLC	Enables standardized text-based communication between pilots and controllers, supplementing or replacing voice communications.	ICAO Doc 9705, Doc 4444 (ATN/OSI protocols)
3. ADS-C	Allows automatic transmission of position reports and surveillance data under predefined contracts, enhancing surveillance in non-radar areas.	ICAO Doc 9705, Doc 4444 (ATN/OSI protocols)
4. FIS	Provides essential flight information such as weather updates and NOTAMs via data link, including services like D-ATIS and D-VOLMET.	ICAO Doc 9705, Doc 4444 (ATN/OSI protocols)

Table 6: Summary of Standardized ATN Air/Ground Applications

These applications use the OSI protocols defined for the ATN, ensuring interoperability and standardization in data communication. While the applications are standardized, their implementation may vary by region and airspace. Some regions have fully implemented these applications, while others may still be in transition. The Future Air Navigation System (FANS)-1/A uses similar applications like CPDLC and ADS-C over the ACARS. However, FANS-1/A is not ATN-compliant and uses proprietary protocols.

The aviation industry is moving towards ATN/IPS, which will use IPv6 protocols. The transition to ATN/IPS is an ongoing process, and clear timelines are established within ICAO Global Air Navigation Plan (GANP)'s Aviation System Block Upgrades (ASBU) framework. Data link applications over ATN/IPS are moving from the standardization phase into implementation, with active trials and initial deployments (see relevant projects in the Appendix).

5 Mobility Management in ATN/IPS

Mobility management is a key feature of the ATN/IPS to ensure service continuity and maintain the connection during handovers. Handover delay, defined as the time taken to re-establish a connection, along with packet loss, latency, and signalling overhead, are critical metrics to assess the handover performance [BaZi11].

As aircraft travel between ANSP networks, data link communication technologies must support a handover mechanism that enables seamless transitions between different access networks based on availability, continuity, and the cost of the data link interface.

The IP protocol was not originally designed for mobile nodes, which poses challenges for mobility management. Consequently, mobility will remain a significant factor in future aeronautical communication networks.

Two mobility challenges are identified in [AlAlNi19]: intra-domain mobility, where the aircraft remains within the same network domain, and inter-domain mobility, where the aircraft changes its network access provider. These scenarios can involve either horizontal handovers, where the same technology is used, or vertical handovers, where the aircraft switches between different technologies (Figure 3).

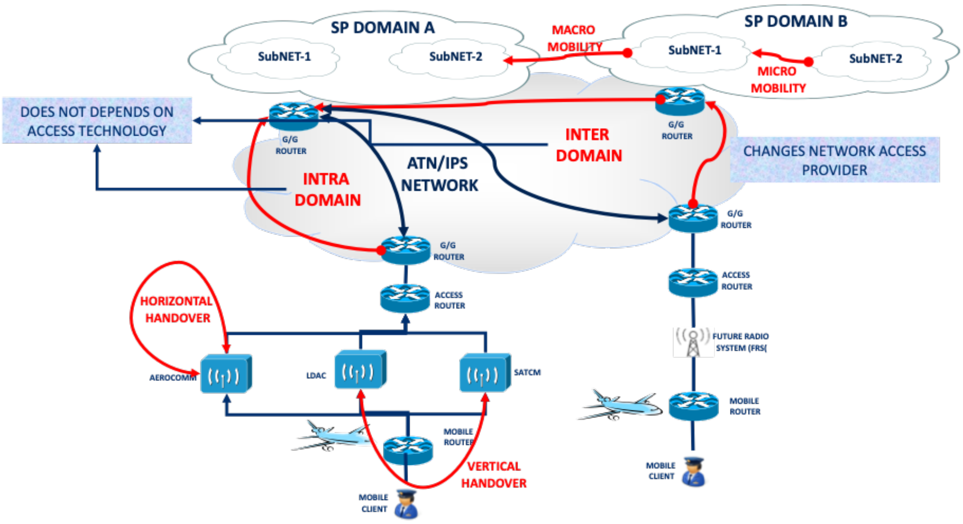

Figure 3: Mobility Scenarios

Table 7 lists key mobility requirements. To fulfill them, the technical, functional, and operational needs of systems or devices that depend on consistent and reliable connectivity during movement must be addressed.

MOBILITY MANAGEMENT REQUIREMENTS	
1. HANDOVER	Sessions must continue seamlessly while the mobile node (MN) moves between different networks or access points
2. REGISTRATION	The network must be aware of the existence and location of the MN
3. CONFIGURATION	The MN must update its IP address dynamically as it moves between networks
4. DYNAMIC ADDRESS BINDING	The MN maintains a constant identifier regardless of its current network attachment point
5. LOCATION MANAGEMENT (IP REACHABILITY)	The network must continuously update location databases

Table 7: Mobility Management Requirements

Understanding the varying levels of mobility and aligning their capabilities with specific application requirements is essential to fulfilling use cases and mobility scenarios. As shown in Table 8, mobility tiers define the extent and type of movement that must be supported.

MOBILITY TIERS	
1. TERMINAL MOBILITY	Allows a device (MN) to maintain its identity and active sessions while roaming between different networks
2. USER MOBILITY	Enables a single user to be addressed by the same logical identity even when using different terminals or devices
3. SESSION MOBILITY	Allows users to maintain active sessions as they move between devices or networks
4. SERVICE MOBILITY	Ensures that users can access the same services across different devices and networks, regardless of in their connectivity even while moving or network service providers.

Table 8: Mobility Tiers

Mobility management can be implemented at various layers of the protocol stack. This section reviews the most notable solutions.

5.1 MIPv6 and Enhancements

One possible mobility solution is MIPv6. However, MIPv6 needs to be adopted for the civil aviation environment. MIPv6 works reliably but produces significant overhead due to mobility signalling [GERA09].

MIPv6 does not support a handover mechanism between different networks [ABEG08]. MIPv6 uses two IP addresses: a home network address and a foreign network address (to locate the aircraft) for a mobile node to allow session continuity during handover. However, MIPv6 suffers latency issues due to the distance between the home agent (HA) and the foreign agent (FA).

Moreover, it faces triangulation (routing) problems that cause end-to-end delays. Mobility signalling and tunnelling between HA and FA also cause overhead issues. Therefore, the mechanism that enables session continuity during handover is not well adapted to the aeronautical environment [TPLB18].

Several enhancements have been introduced to meet mobility requirements and mitigate the drawbacks of MIPv6 [TPLB18]. In the following, we describe four major ones: MIPv6 for local mobility and network mobility (NEMO), Fast handovers for MIPv6 (FMIPv6), and Proxy MIPv6 (PMIPv6).

NEMO defines aircraft as a moving network instead of a moving host over the aeronautical network for global mobility [Schr08]. NEMO has been introduced as an extension of MIPv6 to reduce signalling overhead. In contrast to mobile IP protocols, NEMO does not support route optimization, which provides better end-to-end delay. As a result, delay requirements for some ATS might not be met.

Although HMIPv6 helps reducing signalling traffic during handover within local networks, it suffers from drawbacks in dealing with global mobility, as it requires two IP addresses. Rana, Mandal, and Sardar [RaMaSa15] propose a seamless optimized HMIPv6 that reduces handover latency by almost 91% compared to basic HMIPv6. Due to a seamless mobility management scheme, optimized HMIPv6 may support real-time applications. Wu and Wang [WuWa09] argue that improved handover for the HMIPv6 scheme significantly reduces the handover delay.

While FMIPv6 reduces handover delay and packet loss, the protocol is complex at the network level. FMIPv6 has the potential to evolve into a robust mobility solution with enhanced mobility capabilities, such as vertical handovers, QoS support, and secure handovers [SaJaBe19]. The study in [SuYoYo17], which compares the handover latency, packet loss, and the forwarding cost of MIPv6 and FMIPv6 in low earth orbit satellite networks, reveals that the handover latency of predictive mode FMIPv6, which is triggered when a mobile node enters the coverage area, is lower than the handover latency of MIPv6. Moreover, the study shows that FMIPv6, with its buffering and forwarding mechanisms, outperforms MIPv6 in handover latency, resulting in reduced packet loss. The study concludes that FMIPv6 is more suitable for real-time applications since the impact on handover performance is smaller [SuYoYo17].

Although evaluations show that FMIPv6 and HMIPv6 can significantly improve the handover delay when implemented separately, the performance could be enhanced by integrating FMIPv6 into the HMIPv6 architecture [WuWa09]. The Fast Handover for Hierarchical Mobile IPv6 (F-HMIPv6) scheme, proposed by [JKYL05], is a combination of the Fast Handovers and Hierarchical Mobile IP extensions to MIPv6, which can further reduce the handover latency compared to a simple combination.

PMIPv6 is a network-based solution for local mobility management standardized by the IETF in RFC 5213 [AlAlNi19]. As an aircraft moves within the network service domain, it is assigned a unique IP address, enabling seamless switching without any perceived disruption. This protocol effectively addresses the requirement for local (intra-domain) mobility management [GLDC08]. On the other hand, the mobile node's inter-domain mobility occurs between points of attachment at the edge of the ATN/IPS core network; PMIPv6 is unsuitable because it cannot support multilink and load balancing.

PMIPv6 reduces overhead for mobility signalling compared to MIPv4 and MIPv6 (Figure 4 and Figure 5). It reduces handover delay since signalling is done over wired links. However, it leads to an increased end-to-end delay [ABEG08].

In the PMIPv6 system, when a mobile node enters the PMIPv6 domain for the first time, it must be authenticated. A scheme proposed in [YuZh18] decreases handover delay by 10% and packet loss rate by 11.11% due to authentication without increased throughput.

The scheme in [KiKo11] reduces packet loss by buffering and minimizes network resources by releasing the previous PMIP tunnel in advance. Hussain et al. [HNKU20] state that hybrid and integrated solutions have good potential for enhancing the performance of PMIPv6 extensions in terms of handoff latency, signalling cost, buffering overhead, packet loss rate, and load balancing.

An evaluation in [HOYA21] shows that PMIPv6 offers better throughput, lower latency, and a higher packet delivery ratio than MIPv6.

The study in [MaPi08] shows that FMIPv6 does not effectively reduce the signalling overhead compared to MIPv6 and HMIPv6.

The studies in [MaPi08] and [PeToHa03] show that MIPv6 and HMIPv6 have higher handover latency than FMIPv6.

A performance evaluation of mobile IP protocols conducted in [LBYC13] reveals that FMIPv6 outperforms the other protocols regarding packet loss due to buffering technology employed. It also reveals that PMIPv6 has the lowest signalling overhead.

Performance evaluations in [LeChGu08] and [LeHaGu09] show that PMIPv6 outperforms HMIPv6 regarding signalling overhead and packet loss.

Simulations in [LSSJ09] demonstrate that PMIPv6 is best regarding signalling overhead and handover delay. They also show that MIPv6, HMIPv6, and PMIPv6 have a similar packet loss performance. However, in FMIPv6, buffering is used; thus, packet loss is reduced significantly.

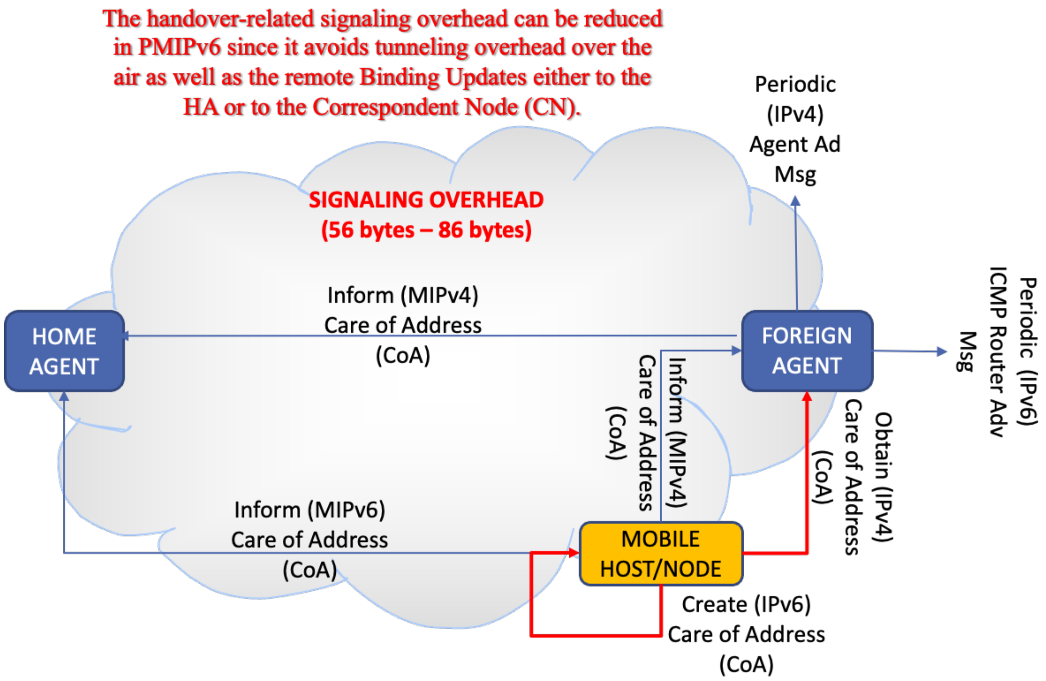

Figure 4: PMIPv6 Signalling Overhead Improvement

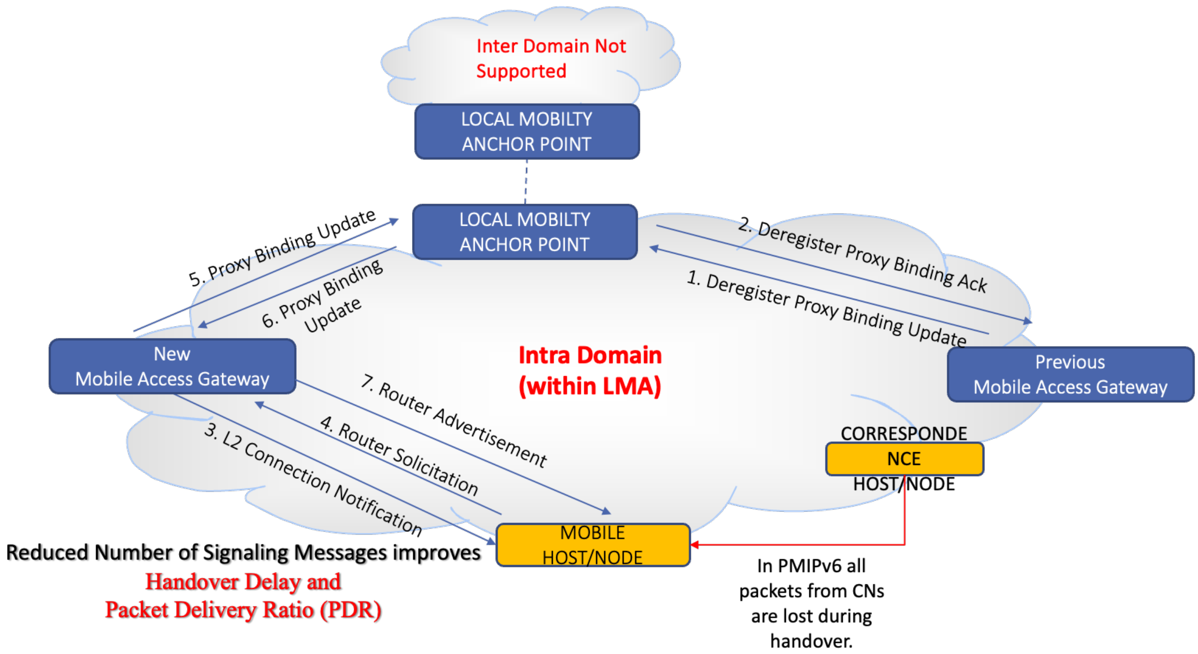

Figure 5: PMIPV6 Signalling Overload Improvement

Table 9 compares the performance of HMIPv6, PMIPv6, FMIPv6, and MIPv6, showing that PMIPv6 is the most suitable enhancement for ATN applications.

Handover Delay	Signalling Overhead	Packet Loss Rate
PMIPv6	PMIPv6	FMIPv6
FMIPv6	HMIPv6	PMIPv6
HMIPv6	MIPv6	HMIPv6
MIPv6	FMIPv6	MIPv6

Table 9: Comparison between PMIPV6, HMIPv6, FMIPv6 and MIPv6. In each column, the protocols are ranked from lowest to highest in terms of the corresponding metric

5.2 Ground Based Locator/ID Separation Protocol (GB-LISP)

The original reason for developing Locator/ID Separation Protocol (LISP) was the routing scalability problems in the Internet core routing. According to the IETF RFC 6831, a key concept of LISP is that end systems (hosts) operate the same way they do today. Hosts' IP addresses for sending and receiving packets do not change [Baue13]. LISP is primarily a routing and addressing protocol that separates endpoint identity and location, helping improve network scalability and efficiency.

LISP [BaRoSa16] is a network architecture and a collection of "map-and-encapsulate" network-layer protocols developed by the IETF "LISP Working Group," as specified in RFC 6830. LISP splits IP addresses into separate numbering spaces: Endpoint Identifiers (EIDs) and Routing Locators (RLOCs), which are dynamically mapped to manage mobility and routing. Splitting EID and RLOC functions yields several advantages, including improved routing system scalability, improved multihoming efficiency, and ingress traffic engineering, as well as making scalability and security capabilities available.

One advantage of LISP is that a location change does not require the change of IP addresses (identity) of host machines [KLHE13]. That leaves room for new ways of operation models in the IP world, like the reachability of mobile systems identified by one single IP address. Routers continue to forward packets based on IP destination addresses. The IP addresses of gateway routers or LISP-capable routers at the edge of end-sites are called RLOCs. In LISP, identifiers and locators can be IP addresses, but other identifiers-locator sets are also accepted, such as a set of MAC addresses and GPS coordinates.

In the context of mobility, LISP can help manage devices' movement across different networks by allowing them to maintain a consistent identity (the Identifier) while their location changes. According to [JaCaDo09], additional mechanisms, such as mobile IP or other mobility management protocols, would typically be required for a device to achieve standalone mobility.

In a multilink context, LISP can choose which network interface address to use for data forwarding based on link performance and availability [KLHE13]. LISP transitions between different networks or interfaces without losing its established sessions. LISP facilitates load balancing by distributing traffic across different paths to optimize bandwidth usage. LISP ensures redundancy and failover by redirecting traffic to alternative operational links, enhancing resilience against link failures. LISP implements path selection algorithms to determine the best network interface address to use at any given time based on metrics like latency, jitter, or link quality. While LISP introduces a framework for multilink functionality, effective implementation may also depend on the configuration and capabilities of the underlying networking equipment and network management protocols.

From a security standpoint in LISP-enabled networks, two methodologies are proposed in [KLHE13] to enhance security: a foundational Virtual Private Network (VPN) setup and an integration of LISP with Group Encrypted Transport VPN (GETVPN) [Cisco12]. LISP inherently offers fundamental VPN capabilities among LISP sites, as EID addresses are not routed within the RLOC address space. Furthermore, registering EIDs in the mapping system necessitates understanding security credentials for a LISP border router. Conventional IPsec technology relies on point-to-point security associations and requires a distinct key for each association, resulting in scalability challenges. GETVPN is founded on IPsec principles, employing a group key to safeguard traffic for all authorized participants [KLHE13]. This method addresses two security concerns: LISP control messages can be protected by GETVPN, eliminating the necessity for further precautions, and LISP data messages transmitting user traffic between LISP locations can be protected for privacy. EID addresses are not transmitted in plaintext via the IP-WAN, which could be problematic if pure GETVPN is used without LISP technology.

While LISP was developed to improve routing efficiency and scalability, Ground-Based LISP (GB-LISP) is a specialized adaptation of LISP for aviation [HaLi16]. GB-LISP is a key component that allows for the full implementation of IP mobility management on the ground. It ensures seamless handover of IP connections as mobile devices move between different network points, maintaining continuous connectivity without disrupting ongoing data sessions. This means that the airborne router is greatly simplified. Moreover, consistent bandwidth optimization over the access subnets can be obtained since the GB-LISP protocol overhead is not transferred through the air interface.

Haindl et al. [Hain24] introduced performance evaluation scenarios and discussed end-to-end performance data obtained from ATN/IPS over the LDACS data link. In this experiment, PMIPv6 was used for local mobility, and GB-LISP was used for global mobility. They concluded that LDACS prototypes fulfilled the performance prerequisites. It should be noted that the LDACS access network and the core network were located within the same laboratory LAN. An increase in latency in the ground network can be anticipated in the case of geographically distributed WAN that would link the air-to-ground routers with the LDACS ground radios. Yu et al. [Yu23] concluded that PMIPv6 in intra-domain and LISP in inter-domain for L-DACS based on LISP may address the global mobility management issues of L-DACS. GB-LISP functionality requires the GB-LISP-specific configuration of one or more GB-LISP-related devices in the network (Figure 6).

Flight trials conducted in [Bell22] demonstrated the ability to establish IPv6-based end-to-end connectivity over LDACS and confirmed successfully secured IPS communication with aeronautical application data.

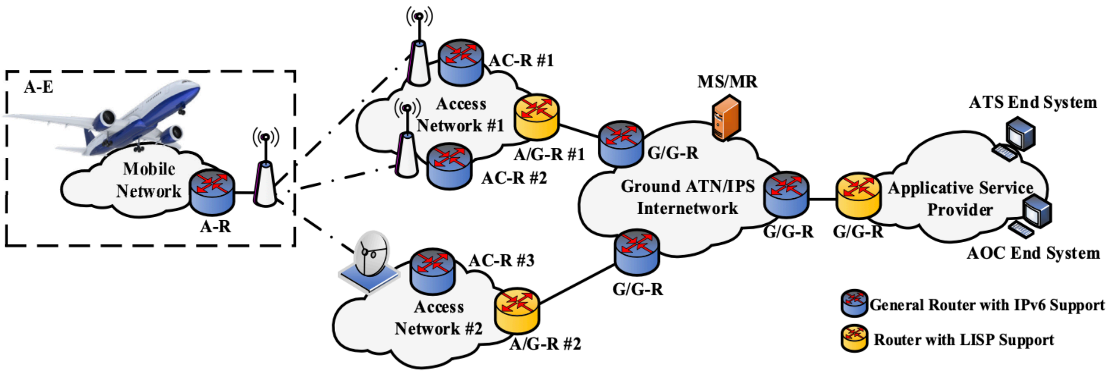

Figure 6: Distribution of sub-networks and global mobility management entities in the FCI system (based on [Yu23])

Virdis, Stea and Dini [ViStDi21] proposed the SAPIENT system and defined an infrastructure that implements multilink functions in IP-based networks, ensuring efficient, scalable, and secure operations. Several approaches for multilink routing were designed. The first option notes that exploiting the standard IP inter-domain routing protocol is not feasible due to its slowness. The second option is based on the NEMO protocol, a tunnelling-based extension of MIPv6, which performs better but remains insufficient for aviation communication due to suboptimal routing and increased latency. The third option, based on LISP, originally proposed for aviation, is considered the best due to its enforcement of multilink selection policies.

In conclusion, as stated in [HaLi16], GB-LISP can provide a transparent multihoming solution for the end systems, allowing load sharing between the different radio technologies dependent on the available QoS. It also solves the aircraft's network mobility problem. Together with GETVPN, it provides a maintainable security solution that does not require different technologies like mobile IP, NEMO, or IPSEC.

5.3 Session Initiation Protocol

The Session Initiation Protocol (SIP) was standardized as IETF RFC 3261. It is an application-layer control protocol that establishes, modifies, and terminates multimedia sessions or calls [BGJK12]. As applied to ATN infrastructure, it facilitates seamless communication between air and ground operations. One key reason for adopting SIP in aviation is its ability to support flexible, real-time communication across different service providers and systems, enhancing efficiency and safety (Figure 7).

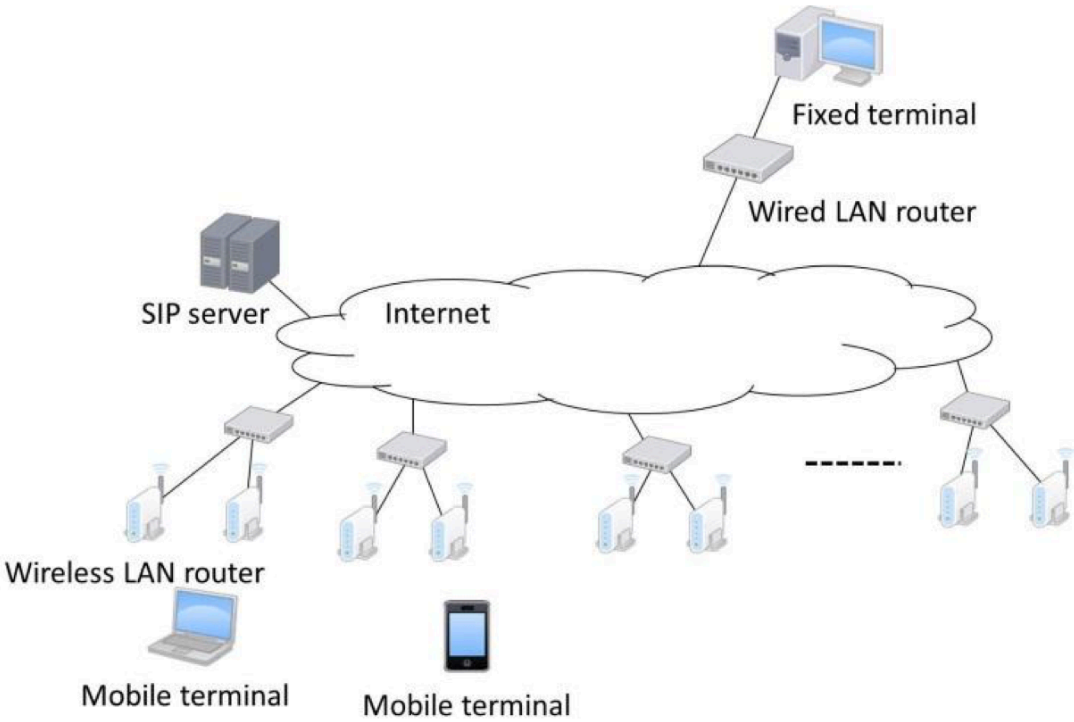

Figure 7: SIP Network Configuration (based on [OdNaTa13])

In particular, the EUROCONTROL-led Voice over Internet Protocol (VoIP) Implementation and Transition Expert Group (VOTE) has supported SIP's use in ATM by developing standards, such as the ED-137, which addresses interoperability requirements for both inter-centre and air-to-ground communication systems in aviation networks. These standards were incorporated by ICAO as part of its guidelines for IPS used in ATM.

Due to the trend of converging voice and data into one multimedia network followed by international and domestic telecom providers, ATM communication networks are gradually developing into a common voice and data services infrastructure [EiKa10]. EUROCAE WG-67 has defined standards for VoIP-based ATC voice communications. According to [EiKa10], the standard protocols SIP and RTP provide all the mechanisms needed to adhere to air-to-ground and ground-to-ground voice communications requirements in ATC.

While PMIPv6 handles mobility locally by enabling devices to roam within a network domain without changing IP addresses, SIP provides global mobility and session management. Song and Jeong [SoJe13] suggest that, along with SIP mobility, a network-based IP mobility management protocol can optimize routes and ensure terminal and session mobility. When a device moves from a PMIPv6 domain into a different network, SIP helps re-establishing sessions across networks. If a user leaves a PMIPv6 network, SIP can facilitate session continuity by redirecting media streams to the new IP location, allowing seamless inter-domain handoffs. By limiting IP address changes and relying on PMIPv6 for local mobility, the architecture reduces the need for global signalling. This makes it particularly cost-effective for large networks and high-mobility environments.

In conclusion, as noted in [SoJe13], PMIPv6-SIP inter-networking ensures seamless session continuity as devices move within and across networks, supporting applications that require uninterrupted connectivity. Terminal-Independent Handover Method with SIP Mobility proposed in [OdNaTa13] improved the throughput by shortening the time spent taking the IP address because the mobile terminal could run communication quickly after a handover. A performance comparison between the SIP-based method proposed in [OdNaTa13] and PMIPv6 is shown in Table 10.

	PMIPv6	**Method in [OdNaTa13]**
Bottleneck	Easy to generate	Hard to generate
Running a handover between different networks	Impossible	Possible
Time taking IP address	Long	Short

Table 10: Comparison between PMIPv6 and the method in [OdNaTa13]

6 Link Selection within Multilink

In a multilink environment, aircraft are equipped with multiple radio access technologies. This section reviews the challenge of selecting the appropriate access network. While this issue has been thoroughly studied in traditional mobile wireless networks [YoJa13], [KaYo16], [WCAC17], [NgNgWh18], [HoZoMo22], [ATMM22], [RCKJ23], it has received comparatively less attention in the context of aeronautical communications.

Optimizing data link selection is critical for ensuring efficient, reliable, secure, and cost-effective communication. However, the process is challenging due to the wide range of criteria (attributes) and constraints involved. Key attributes include link quality, QoS requirements, link costs, and resource utilization. Key constraints include the type of communication service, the application in use, security requirements, and the preferences of both users and operators.

In [AHPX17], a terminal node (TN) onboard the aircraft collects information about available data links. The TN consists of two main subsystems: the routing subsystem (RoS) and the radio subsystem (RaS), both equipped with multiple data links. Four types of radio links are considered: Inmarsat Broadband Global Area Network (BGAN) Class 4 and Class 6, VDLm2, and Iridium. The paper [AHPX17] proposes two data link selection methods: a baseline method and an optimized method. The baseline method uses a predefined data link priority list based on a single attribute to select the data link. The optimized method, on the other hand, uses a multiple attribute decision-making (MADM) algorithm. An essential step in MADM is assigning weights to the attributes to specify their relative importance. The authors use both objective and subjective weights in their approach. The objective weights are calculated using a variance-based method, while the subjective weights are automatically computed by an algorithm that reflects user preferences. This algorithm is based on a trigger-based automatic subjective weighting (TRUST) method. Finally, using the calculated weights, the simple additive weighting MADM algorithm is used to select the appropriate data link. The performance of the optimized method is evaluated through simulations using bit rate, packet delay, bit error rate, relative link costs, resource matching factor, and received signal strength as attributes. Both real-time and non-real-time applications, as well as safety and non-safety services, are considered.

In [ZeGiPh19], a performance-based multilink (PBM) approach is proposed to optimize the use of multiple data links. PBM is based on multilink status tracking, multilink serial utilization, multilink parallel utilization, and global mobility. Operators can specify their subnetworks and Data Service Provider (DSP) preferences in advance. PBM monitors subnetwork status, notifying the ground system of changes, such as link establishment or loss. For message transmission, PBM selects the most suitable available subnetwork. In serial utilization, messages are sent over multiple links sequentially, switching to the next available preferred link if no acknowledgment is received within a set time. Parallel utilization transmits messages over multiple links simultaneously. When an aircraft leaves a subnetwork's coverage, both the aircraft and ground system stop using that link. When the service application sends a message to PBM, PBM determines whether a single link can meet the service performance requirements. If so, the message is sent over a single link. Otherwise, PBM selects the smallest number of parallel links to satisfy the requirements and transmits the message simultaneously over these links.

Wang et al. [WHDW18] first address the data link selection problem for a single user (aircraft). The objective is to select the data link that maximizes both the user's multiattribute utility (user-side objective) and the highest access rate (network-side objective). This multiobjective optimization problem is converted into a single-objective optimization problem using linear scalarization and is solved through integer programming. However, due to limited resources, the single-user solution cannot be applied when multiple users compete for the same data links. In the multiuser scenario, the multiobjective optimization problem is transformed into a max-min problem using the weighted Tchebycheff method. Since finding the optimal solution to the weighted Tchebycheff problem is computationally expensive, the authors propose a Priority Distinction Selection (PDS) algorithm. The goal of the PDS algorithm is to maximize the number of users accessing their optimal data links. Although the PDS algorithm is computationally efficient, it does not guarantee an optimal solution. In a Software-Defined Networking (SDN) environment with centralized control, the network receives access requests from all users and then optimizes these requests using the PDS algorithm. The two data link selection algorithms are evaluated through simulations, using Iridium, VDLm2, Inmarsat's Broadband Global Area Network (BGAN), and the Mobile User Objective System (MUOS) as available links for aircraft in overlapping airspace. The simulations consider bit rate, packet delay, received signal strength, and cost (CST) as attributes.

Wang et al. [WWDH19] consider a framework where aircraft can connect to ground base stations via three modes: single satellite link mode, single line-of-sight (LOS) link mode, and dual connectivity (DC) mode, where the aircraft is simultaneously connected to both a satellite link and an LOS link. They introduce an SDN controller, which manages the connection mode for each aircraft. For every aircraft in a given timeslot, the maximum transmission rates for both the satellite link and the LOS link are provided. Based on these data transmission rates, the controller enables flexible traffic scheduling. To ensure user fairness and adhere to limited resource constraints, a stochastic optimization problem related to handover overhead is formulated, considering queue backlog. The authors use Lyapunov optimization theory to solve this problem, transforming the stochastic optimization problem into a deterministic one for each timeslot. They propose three strategies to address this optimization and validate their approaches through simulations. These simulations are conducted in two scenarios: one using a VDL and a GEO satellite data link, and the other using a VDL and an LEO satellite data link. In both cases, they assume an environment with 80 aircraft in overlapping airspace.

As part of the Horizon 2020 Cockpit Network Communications Environment Testing (COMET) project, Luong et al. [LHLA20] examined the link selection problem in a multilink ATN environment. The COMET system considers various radio access technologies, including VDLm2, AeroMACS, LDACS, and SATCOM. The ground segment includes an SDN Ground (SDN-G) controller and a Ground End System. Multiple aircraft request communication with Ground End System. Each aircraft can use one of the four air-to-ground data links, with each data link having its own transmission characteristics in terms of data rate capacity, transmission delay, packet loss rate, and cost. The SDN-G controller assigns a data link to each transmission request. The multilink selection problem is formulated as finding the assignment that maximizes a total utility function, which is based on the transmission characteristics. Luong et al. [LHLA20] proposed two methods to solve the problem. The first method uses exhaustive search to find an optimal solution but has high time complexity. The second method uses a deep learning model to find a high-quality solution with much lower time complexity. In [LAHL21], the framework is extended and two additional algorithms based on simulated annealing are proposed.

In the Clean Sky 2 Joint Undertaking (JU) GAM-2020-LPA project [SOEM21], a multilink environment was simulated using a SATCOM link and an IPS-enabled VDLm2 link. Link selection was based on decision rules outlined in Table 11. Only the decision rules for traffic class CS4 with a DSCP value of 32 were used. This traffic class is specifically designated for CM and CPDLC applications [ICAO9896]. The first available link was selected, and the second link was used only if the first was unavailable.

Flight Phase		Preferred Data link for CS4 Traffic Class	
		1st Preference	2nd Preference
1	Preflight	VDLm2	SATCOM
2	Taxi out	SATCOM	None
3	Take off	SATCOM	None
4		SATCOM	VDLm2
5		SATCOM	VDLm2
6	Climb	VDLm2	SATCOM
7		VDLm2	SATCOM
8	Cruise	SATCOM	VDLm2

Table 11: Link Selection Rules for Traffic Class CS4 [SOEM21]

The multilink solution proposed in the SESAR 2020 PJ14 Wave 2 Solution 77, "FCI Services" [SESAR23] supports the integration of LDACS, SATCOM, IP VDLm2, and AeroMACS. This solution provides ATN/IPS multilink capability and enables aircraft mobility across different data link systems. It is currently the only solution validated up to TRL6. Two scenarios are considered: performance-based policy and administrative policy. In the first scenario, link selection is guided by the quality required to meet the performance levels of specific applications. When two different services are transmitted over the same data link, prioritization is applied based on the QoS configuration. The goal is to maximize not only performance but also availability of the service. In the second scenario, link selection is based on predefined policies or preferences. These policies can be mandatory or recommended, with preferences potentially set by Air Traffic Service Providers (ATSP) or the airspace user. Selection criteria may include geographical location, altitude, airspace region, or phase of flight.

The multilink solution requires two interface protocols: GB-LISP and the Air/Ground Mobility Interface (AGMI). GB-LISP was discussed in Section 5. AGMI allows IPS-enabled aircraft to communicate with the ground IPS-enabled mobility network, providing both the status of each data link in use and the link preferences as configured in the aircraft's IPS system by the aircraft operator [SESAR23]. Both GB-LISP and AGMI are standardized in Edition 3 of ICAO Doc 9896.

7 Challenges and Open Problems

Mobility management in ATN/IPS addresses both intra-domain and inter-domain mobility scenarios [Yu23]. Research supported by the SESAR Project recommends PMIPv6 for managing intra-domain mobility [MaGrSc23] and GB-LISP for inter-domain mobility [SESAR23]. However, the adoption of PMIPv6 and GB-LISP in ATN/IPS presents potential drawbacks, which are discussed in the following sections.

7.1 Proxy Mobile IPv6 (PMIPv6)

PMIPv6 primarily focuses on mobility management. Its main purpose is to enable seamless handovers as mobile nodes move between network access points while maintaining IP connectivity.

However, despite being one of the more attractive alternatives among MIPv6 enhancements (as discussed in Section 5.1), PMIPv6's reliance on a single Local Mobility Anchor (LMA) introduces a potential single point of failure, which raises concerns about its suitability for mission-critical services in the FCI. In the aviation environment, where rapid changes in connectivity are common as aircraft move between networks, these limitations could adversely affect the user experience during handovers.

While PMIPv6 does not inherently support multilink configurations, it can be adapted to work with multilink environments through the integration of additional mechanisms such as Multipath TCP. To achieve effective multilink functionality, key aspects like network architecture, signalling, and session management must be carefully designed.

Standard PMIPv6 does not natively support route optimization, but extensions such as localized routing, the integration of Distributed Mobility Management (DMM), which distributes mobility management functions across multiple nodes within the network, and Software-Defined Networking (SDN) can significantly improve routing efficiency [BAAGS17].

Implementing PMIPv6 in an aviation context can be complex due to the need to integrate diverse network technologies and ensure seamless interoperability.

7.1.1 Mobility Management

Despite several advantages of PMIPv6 for mobility management, it may face drawbacks in certain aviation scenarios. PMIPv6 involves signalling between intermediate nodes, such as the Mobile Access Gateway (MAG) and the Local Mobility Anchor (LMA), as illustrated in Figures 5.2 and 5.3. This signalling introduces overhead, which may negatively affect performance, especially during frequent handovers. Although PMIPv6 is designed to minimize handover delay, updating location information during mobility events can introduce latency.

Designed as a network-based mobility protocol (Figure 8), PMIPv6 abstracts mobility management from the mobile node. This means that the mobile node does not participate in handover decisions. While this simplifies mobility for the node, it can result in suboptimal handover decisions, especially in dynamic network environments where signal strength, latency, or QoS may vary rapidly.

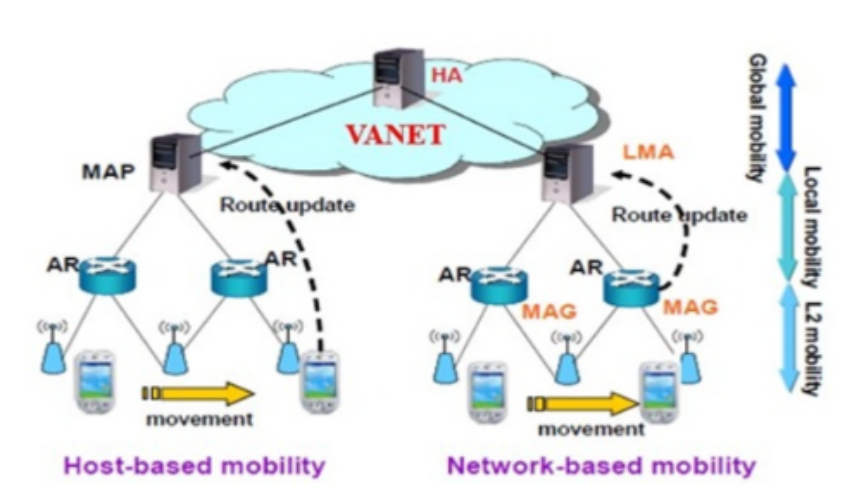

Figure 8: Host-based vs. network-based mobility management protocols (based on [HMOE15])

PMIPv6 has limitations in handling multicast traffic, which can be a significant drawback for applications that rely on multicast communication. As the number of mobile nodes increases, the load on intermediate nodes can become a bottleneck, potentially impacting the scalability of PMIPv6.

PMIPv6 provides terminal mobility, allowing a mobile terminal to retain its IP address and maintain active sessions and connections without interruption.

7.1.2 Session Management

PMIPv6 focuses solely on mobility management. Separate session management protocols (e.g., SIP) are needed to handle application-layer sessions. These protocols operate at a higher layer and are responsible for managing the setup, modification, and termination of communication sessions.

7.1.3 Connection Management

PMIPv6 does not directly manage connections like traditional transport protocols. It maintains IP continuity during mobility, while connection-oriented protocols handle the actual connection management at the transport and application layers.

7.1.4 Security

PMIPv6 does not inherently provide security features, so additional security protocols are needed to protect communication and ensure authentication, confidentiality, and integrity in the network.

7.1.5 Performance

Numerical results demonstrate that PMIPv6, which relies on network-based mobility management, generally performs better than host-based mobility protocols such as MIPv6, FMIPv6, and HMIPv6 in cellular networks. PMIPv6 typically shows better throughput, lower latency, and reduced handover delay compared to MIPv6 and its enhancements, due to its ability to offload mobility management to the network. However, PMIPv6 should be extensively evaluated for high-mobility and high-latency environments like SATCOM, where long propagation delays and rapid connectivity changes may impact its performance. Table 12 presents performance characteristics of PMIPv6.

Since PMIPv6 is designed for local mobility, the work in [AlAlNi19] proposes two solutions to enable global mobility in aeronautical communications: a combination of MIPv6 and PMIPv6, and a combination of GB-LISP and PMIPv6. Both solutions are evaluated in terms of handoff latency. For intra-domain handover, which is handled by PMIPv6, there is no significant difference in performance between the two solutions. However, for inter-domain handover, the LISP-based solution is more promising than the MIPv6-based solution, providing faster handovers and better end-to-end delay performance.

Signalling Overhead	Signalling Overload	Handover Delay	Handling Packet Loss	End-to-End Delay	Tunnelling Overhead
72 bytes	Needs to be reduced in high mobility scenarios	Better performance required for high mobility scenarios	No	Better performance required for high mobility scenarios	12 to 20 bytes

Table 12: PMIPv6 Performance

7.2 Ground-based Locator/ID Separation Protocol (GB-LISP)

GB-LISP adds complexity to the network architecture by separating locators (RLOCs) and identifiers (EIDs) [Aias13]. Integrating GB-LISP into aviation networks requires significant modifications to existing protocols and infrastructure, which can be both challenging and costly. Given that GB-LISP is a relatively new protocol, and not all devices or network equipment support it natively, its adoption could be hindered, making integration into existing aviation systems difficult and potentially causing interoperability issues with legacy systems.

Understanding the implications of GB-LISP in aviation networks is crucial. While GB-LISP offers advantages, particularly in terms of scalability and mobility management, its implementation requires a thorough assessment of the associated challenges and potential drawbacks.

To improve routing scalability and facilitate flexible address assignment in multilink scenarios, GB-LISP introduces changes to the Internet architecture. RLOCs replace traditional IP addresses for global Internet routing, while EIDs are used to identify network sessions between devices. However, previous studies like [MeKlHa10] highlight LISP's shortcomings, including unnecessary mapping lookups, path stretch, and double encapsulation headers. Recent studies, such as those in [SuKi20], suggest caching mechanisms at LISP routers and enhanced LISP Mapping Systems to address these issues.

As noted in [JaCaDo09], LISP does not inherently support mobility. An external overlay mechanism is required to provide mobility, such as the LISP-MN (LISP Mobile Node) solution [WLMF16]. This approach simplifies mobility across independent domains by adding a layer on top of LISP, enabling mobility support. Thus, LISP complements mobile-aware systems by enhancing routing efficiency and facilitating seamless mobility but does not provide standalone mobility.

LISP-enabled routers developed by Cisco [Cisco12] should be integrated into the FCI network reference architecture to support multilink and other LISP-specific features (Figure 9). Although LISP is implemented in Cisco routers, LISP RFCs are still in the experimental stage. However, LISP is on the IETF’s standardization track, with a target completion date of November 2026.

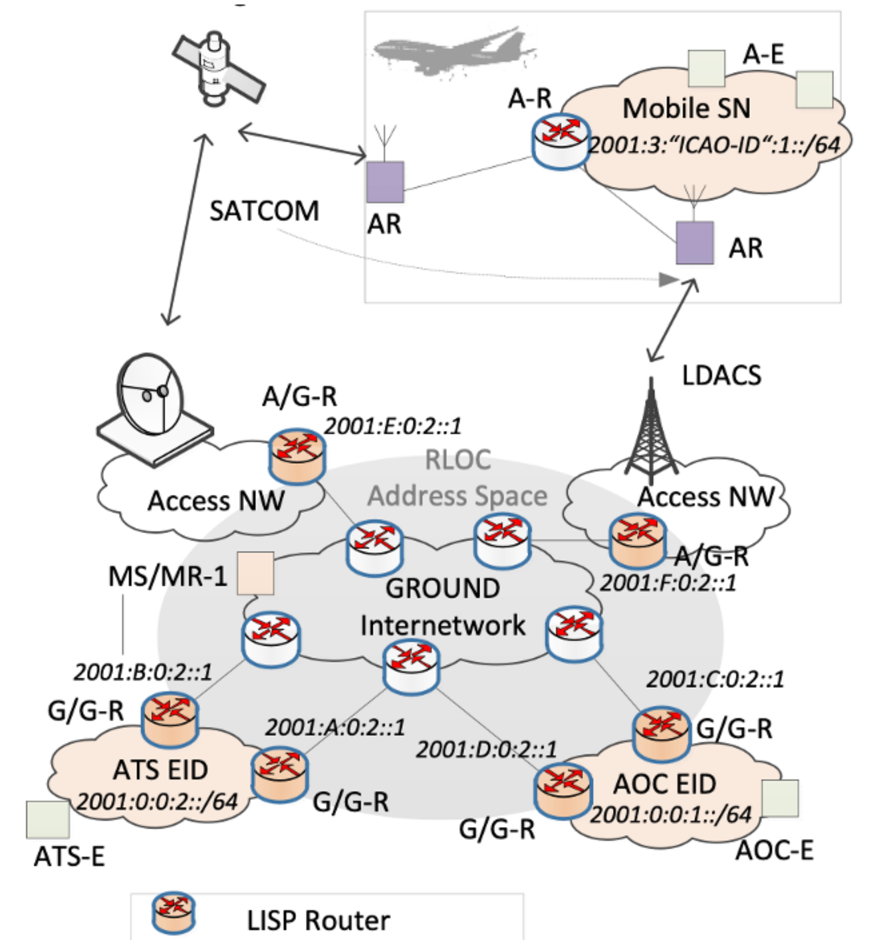

Figure 9: LISP Network Configuration (based on [OdNaTa13])

7.2.1 Mobility Management

Terminal mobility is essential in an aviation environment where it is critical to maintain continuous sessions while on the move. Although LISP can provide a form of terminal mobility, it is not specifically designed for this purpose. As discussed in [MeKlHa10], through a mechanism known as LISP-MN, LISP can support mobile endpoints by allowing them to retain stable EIDs, while their RLOCs change as they move across different networks. This approach enables a mobile node to update its location without requiring a new IP address, effectively supporting mobility.

However, LISP's mobility support is less seamless than traditional terminal mobility protocols, like Mobile IP, which are specifically designed to handle device movement and ensure seamless connectivity. In contrast, the LISP-MN mechanism can suffer from issues such as long service disruption times (SDT) and packet loss, which can degrade network performance and impact applications requiring real-time data transmission, such as voice or critical flight information exchange [ISSE17].

7.2.2 Session Management

GB-LISP does not provide session management features, such as establishing, modifying, or terminating sessions. It is a network-layer protocol designed primarily to separate locators (RLOCs) and identifiers (EIDs) to enhance routing scalability and mobility. To properly manage sessions, GB-LISP must be used in conjunction with other session management protocols and mechanisms, such as SIP. As a result, GB-LISP does not function as a standalone solution for session management.

Integrating GB-LISP into an existing session management framework can introduce additional complexity, requiring careful planning and coordination with other network components. Since GB-LISP operates at the network layer and abstracts this from the application layer, session management responsibilities must be handled by the application or higher-layer protocols.

GB-LISP does not provide session management, such as establishing, modifying, or terminating sessions. GB-LISP must be used with other session management protocols and mechanisms to manage sessions properly. Hence, it does not serve as a standalone solution. Integrating GB-LISP into an existing session management framework might introduce additional complexity, requiring careful planning and implementation. Since GB-LISP operates at the network layer, session management responsibilities must be handled by higher-layer protocols, such as those at the application or transport layers.

7.2.3 Connection Management

GB-LISP does not provide features specifically aimed at connection management, such as connection establishment, teardown, or state maintenance. Effective connection management typically relies on additional protocols, such TCP for transport layer connections or signalling protocols for session control, which are outside the scope of GB-LISP. Integrating GB-LISP into an existing connection management framework may introduce complexity as it would require aligning it with these higher-layer protocols and could necessitate significant changes to the network infrastructure.

7.2.4 Security

The study in [KLHE13] highlights the weakness of clear-text transfer of LISP data and control messages over IP WAN, which could allow potential attackers to gain insight into the identity of EIDs behind a LISP site and determine which RLOCs can be used to reach those EIDs. According to [BaRoSa16], if encryption is necessary, GETVPN [Cisco12] can be used to secure the traffic. However, using GETVPN with Cisco routers makes the LISP network proprietary, as GETVPN is a Cisco-specific solution.

7.3 Session Initiation Protocol (SIP)

Although SIP can provide both connection and session management in addition to mobility management at the application layer, in the context of aviation, its potential for delays can impact the responsiveness of aeronautical communication systems. SIP communications can suffer from packet loss and jitter, which degrade voice quality. This is particularly problematic in aeronautical communications, where voice clarity is essential for safety and coordination. Aviation applications, especially those related to ATC and cockpit communications, require low-latency, real-time interactions. SIP may introduce latency due to signalling overhead, which can negatively affect the performance of critical communication systems. Due to delays in session setup and handover processes, SIP's typical operation may not be optimized for rapid mobility scenarios in aviation.

SIP-based systems are also vulnerable to cyber threats, such as Denial of Service (DoS) attacks, eavesdropping, and spoofing [WKPF09]. These attacks can lead to service interruptions and unauthorized access to sensitive communication, posing serious security risks in aviation. As mentioned in [ZhWaHe12], SIP is independent of the underlying network transport protocols and media types. However, SIP does not have built-in QoS mechanisms; instead, it relies on the underlying IP networks to prioritize traffic. The RTP/RTCP protocol, which SIP uses, is designed for interactive media types such as voice, video, and other real-time multimedia applications, with QoS parameters extracted from RTP packets. Maintaining consistent QoS for SIP sessions can be challenging in the high-mobility aviation environment, where aircraft frequently switch between networks.

SIP supports advanced mobility management, where user identification is based on a Uniform Resource Identifier (URI), and user location is determined by URI. The handover procedure occurs at the application layer, and handover performance is generally good for UDP-based real-time applications [LCSJ09]. However, as a text-based protocol operating at the application layer, SIP's messages are extensive, which can lead to longer handover delays. While SIP excels in mobility management for SIP-based applications, it falls short in supporting non-SIP-based applications, especially non-real-time ones. Furthermore, SIP lacks built-in security mechanisms, which is a serious issue in wireless and mobile environments. Table 13 summarizes the findings of this section.

		PMIPv6	GB-LISP	SIP
IP REACHABILITY		YES	YES	NO
LOCATION UPDATE		YES	YES	YES
SESSION CONTINUITY		YES	YES	YES
MULTILINK SUPPORT		NO	YES	NO
SECURITY SUPPORT		YES	YES	NO
QoS SUPPORT		YES	YES	NO
MOBILITY SUPPORT	INTRA MOBILITY	YES	NO	YES
	INTER MOBILITY	NO	YES	YES
MOBILITY MANAGEMENT	TERMINAL MOBILITY	YES	YES[2]	YES
	USER MOBILITY[1]	N/A	N/A	YES
	SESSION MOBILITY[1]	N/A	N/A	YES
	SERVICE MOBILITY[1]	N/A	N/A	YES
SESSION MANAGEMENT		NO	NO	YES
CONNECTION MANAGEMENT		NO	NO	YES

Table 13: PMIPv6, GB-LISP and SIP Comparison

Note 1: Specific application and service implementation or protocol implementation required
Note 2: Needs a mechanism known as LISP-MN

In conclusion, reducing handover delays and signalling overhead is essential for the effective adaptation of SIP in aviation.

Co-funded by the European Union

8 Conclusions

The increasing demand for seamless connectivity in aviation requires robust and efficient mobility management solutions. However, current protocols such as PMIPv6, GB-LISP, and SIP, while offering certain advantages, have limitations that hinder their effectiveness in the dynamic and demanding aviation environment.

Mobility Management Limitations

User Mobility:

- **PMIPv6 and GB-LISP**: These protocols primarily focus on terminal or network-based mobility, which ensures that devices (or nodes) maintain IP connectivity during movement. However, they lack inherent support for user mobility, which allows users to maintain a consistent identity and access personalized services across different devices and networks. This limitation means that, although devices can remain connected, user-specific settings and services may not seamlessly transition between devices and networks.

Session Mobility:

- **PMIPv6 and GB-LISP**: While these protocols handle network mobility, their support for session mobility—ensuring ongoing communication sessions remain uninterrupted across network transitions—is limited. In high-mobility scenarios, this can lead to disruptions in active communication sessions during handovers.
- **SIP**: SIP supports session mobility at the application layer, allowing sessions to continue during network transitions. However, it suffers from signaling overhead and latency issues, which can degrade the quality of service, especially during handovers in high-mobility environments.

Service Mobility:

- **SIP**: SIP enables service mobility, which ensures continuous access to services across different networks and devices. This is a key advantage in environments requiring seamless service transitions. However, SIP’s performance can be compromised in high-mobility environments due to its signaling overhead and limited built-in QoS capabilities, which may affect service quality during rapid network changes.

Limitations of Current Protocols

PMIPv6 and GB-LISP:

- **Limited Session and Connection Management**: These protocols focus on mobility management, primarily ensuring devices maintain IP connectivity as they move. However, they lack native support for session management (e.g., the establishment, modification, and termination of communication sessions) and connection management (e.g., maintaining transport-layer connections), necessitating the use of additional protocols like SIP. This added complexity introduces overhead and can lead to higher latency during transitions.
- **Security Concerns**: While security features can be implemented as add-ons, neither PMIPv6 nor GB-LISP provide inherent security mechanisms. This makes these protocols vulnerable to various cyber threats such as data interception and denial-of-service (DoS) attacks.

SIP:

- **Signaling Overhead and Latency**: SIP's text-based signaling introduces significant overhead, leading to delays during session setup and handovers. This is especially problematic for real-time communication, where low latency is critical for services like air traffic control.
- **Limited QoS Support**: SIP's QoS capabilities rely on the underlying network, which can make it difficult to guarantee the quality of service for critical aviation applications. This is a significant limitation in environments where network conditions can vary rapidly.
- **Security Vulnerabilities**: SIP is susceptible to various security attacks, including DoS, eavesdropping, and spoofing, which can compromise the integrity and confidentiality of communications. Aviation environments demand higher security assurances to protect against such threats.

Recommendations for a New Protocol

To address the limitations of current protocols and meet the specific needs of aviation, a new protocol should incorporate the following features:

- **Integrated Session and Connection Management**: Native support for session and connection management would reduce complexity and latency by avoiding reliance on separate protocols. This would ensure that sessions are maintained across transitions without the need for external mechanisms.
- **Robust QoS Mechanisms**: Built-in QoS capabilities are essential to guarantee consistent service quality, especially for time-sensitive applications.
- **Enhanced Security**: The protocol must include strong, native security features to protect against cyber threats, ensuring data confidentiality, integrity, and authentication across communication channels.
- **Seamless Mobility Management**: Efficient mobility management is required to handle both user and session mobility. The protocol should allow users to maintain a consistent identity across devices and ensure that active sessions remain uninterrupted across network transitions. Furthermore, it should enable service mobility, allowing seamless access to services regardless of network changes, while maintaining service quality.
- **Flexibility and Adaptability**: The new protocol must be flexible enough to adapt to evolving network technologies and changing operational requirements in aviation, ensuring scalability and futureproofing.

Appendix A Relevant Projects

The Single European Sky ATM Research (SESAR) programme is a collaborative initiative aimed at modernizing and harmonizing ATM across Europe. A critical aspect of this modernization involves enhancing data link communications to improve efficiency, safety, and capacity. The following table provides an overview of key SESAR projects focused on data link communication technologies and solutions. By developing and integrating new technologies such as LDACS, satellite-based VHF communications, these projects aim to enhance communication capabilities between aircraft and ground systems.

Project Name	Duration & Status	Objectives	Project Link	Web Link
SAPIENT - Satellite and Terrestrial Architectures Improving Performance, Security, and Safety in ATM	01/04/2016 – 30/09/2017 Status: Completed	Explored innovative applications in CNS, focusing on improvements to air-ground data links and integration of remotely piloted aircraft systems (RPAS) flying beyond line-of-sight missions. Provided a new communication application for future CNS/ATM systems.	Project Link	N/A
PJ14 EECNS - Essential and Efficient Communicatio n, Navigation, and Surveillance Integrated System	01/11/2016 – 31/12/2019 Status: Completed	Specified and developed future CNS technologies to support and manage operational services like 4D trajectory management in the future ATM system.	Project Link	N/A
PJ15 COSER Common Services	01/11/2016 – 31/12/2019 Status: Completed	Research into multi-link communication systems and improved data link protocols. Develop advanced air-ground communication technologies, including data link enhancements, to support future ATM concepts. Develop the LDACS as a secure, high-capacity data link technology.	Project Link	N/A
PJ14-W2 I-CNSS - Integrated Communicatio n, Navigation, and Surveillance System (Wave 2)	01/12/2019 – 30/06/2023 Status: Completed	Continued the development of future CNS technologies to support operational services like 4D trajectory management in the future ATM system.	Project Link	N/A
SINAPSE - Software Defined Networking Architecture	01/05/2020 – 31/10/2022	Proposed an intelligent and secure aeronautical data link communications network architecture based on Software Defined Networking (SDN) augmented with Artificial Intelligence (AI) to predict and prevent safety service outages, optimize network resources, and	Project Link	N/A

Augmented with Artificial Intelligence	Status: Completed	implement cybersecurity functions against digital attacks.		
FACT - Future All Aviation CNS Technology	01/07/2020 – 31/12/2022 Status: Completed	Evaluated and demonstrated performance-based integrated communication, navigation, and surveillance (iCNS) using cellular networks such as 4G and 5G as complements to existing CNS technologies. Supported airspace management and U-space services.	Project Link	Website
PJ33-W3 FALCO - Flexible ATCO Endorsement and LDACS Complement	01/01/2021 – 30/06/2023 Status: Completed	Investigated solutions to make ATM and the deployment of air traffic controllers more flexible, cost-efficient, and responsive to changing traffic demands. Trialled LDACS for spectrum-efficient data link connectivity and digital voice communications between air and ground.	Project Link	N/A
VOICE - Reduced Separations and Improved Efficiency Based on VHF Communications Over LEO Satellites	01/01/2021 – 30/06/2023 Status: Completed	Demonstrated satellite-based VHF systems providing voice and data link ATS for remote airspace. Aimed to reduce separations without compromising safety while maintaining conventional ATS.	Project Link	N/A
ECHOES - Extended Communications in VHF Over Enhanced Satellite Segment	01/03/2022 – 28/02/2025 Status: Ongoing	Demonstrating the technical feasibility of a space-based solution for VHF communications (voice and data link) for aviation. Developing and launching two Low Earth Orbit satellites to test technologies aimed at improving Air Navigation Services, focusing on oceanic areas.	Project Link	N/A
MIAR - Making I-CNSS a Reality	01/06/2023 – 31/05/2026 Status: Ongoing	Carrying out flight tests to demonstrate how LDACS can enable optimised separation between aircraft in real time and using multiple non-GNSS technologies for an integrated navigation solution.	Project Link	Website
FCDI - Future Connectivity and Digital Infrastructure	01/06/2023 – 31/05/2026 Status: Ongoing	Developing future communications, navigation, and surveillance technologies to support and manage operational services like four-dimensional trajectory management in the future ATM system. Focus areas include: - Collaborative Cyber Security Framework for CNS: Elevate trust and safety. - Hyper Connected ATM Precursor: Enable safe and secure use of public communication links. - FCI Services and IPS Enhancements: Enhance mobility and multilink for safer, interoperable aviation.	Project Link	N/A

		- FCI Terrestrial Data Links – LDACS: Provide secure, high-throughput communication capability and voice with embedded navigation capability.		
CNS DSP - Demonstration of a CNS Data Service Provision	01/09/2023 – 31/08/2026 Status: Ongoing	Developing digital platforms and services leveraging state-of-the-art technologies to enable future data-sharing service delivery models. Aims to share CNS data between ANSPs and other aviation stakeholders like civil and military airspace users, airports, and national authorities.	Project Link	N/A
ESMA European Sky Multilink ATN	01/01/2024 – 31/12/2026 Status: Ongoing	ESMA will address the need to increase the level of automation in ATM through the implementation of a multi-link communications infrastructure, with a focus on data link using SATCOM Data link alongside VDLm2. The demonstration will focus on long-term data collection in an operational multi-link environment to demonstrate that technology meets the technological requirements and business needs of air navigation service providers and airspace users.	Project Link	N/A
ASTONISH - Alternate Surveillance Technologies for Innovative Solutions	01/09/2024 – 28/02/2027 Status: Ongoing	Developing new surveillance solutions using innovative technologies for airborne and ground traffic management. Investigating: - Ground-Based Systems: For en-route and terminal area surveillance. - Aircraft-Based Alternate Surveillance (A-SUR) Technology: Enhancing onboard surveillance capabilities. - Airport and Aircraft-Based Surveillance Sensing Systems: For ground operations.	Project Link	N/A

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