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RESEARCH ARTICLE

Comparative Analysis of Multi-Link Selection Strategies for Next-Generation Aeronautical Communications

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ABSTRACT Next-generation aviation demands seamless connectivity across heterogeneous networks, yet maintaining uninterrupted links under strict performance requirements remains a major challenge. Current Aeronautical Telecommunication Network (ATN) mechanisms depend on static tables that overlook airframe shadowing and dynamic flight conditions, limiting their effectiveness in complex radio environments. This paper delivers a comprehensive evaluation of terrestrial and non-terrestrial networks (NTN) and benchmarks twelve link-selection algorithms across representative Air-to-Satellite (A2Sat) and Air-to-Ground (A2G) scenarios. The system design introduces an AI-driven dual-layer onboard controller that integrates predictive planning with real-time adaptation. Simulation results show that this approach enables proactive link switching, enhances stability, and supports efficient flight operations. To sum up, this work can be a roadmap for ATN architectures by delivering resilient, hyper-connected communications required for next-generation aviation and paves the way for this implementation.

INDEX TERMS Aeronautical communications, multi-link, decision-making, aeronautical telecommunication network.

I. INTRODUCTION

The aviation sector is shifting to digital, highly connected, data-intensive operations [1]. The future of airborne communication is set to be revolutionized by an interconnected ecosystem that integrates Unmanned Aircraft System (UAS), manned aircraft, satellites, and ground stations to enable continuous, real-time data exchange [2], called Unmanned Aircraft System Traffic Management (UTM). The global UTM system market is projected to reach \$3.62 billion by 2026 [3]. This growth is fueled by several factors, including the rapid expansion of unmanned aircraft operations, heightened interest from governments, and the emergence of new regulatory frameworks. A UTM system is designed to collect and process traffic data (flight trajectories, real-time locations

of all Unmanned Aerial Vehicles (UAVs) to then automate safe and efficient airspace management [4] and the concept of U-Space [5] talks about the services flying aircraft could use. Air Traffic Management (ATM) 2.0 [6] represents a paradigm shift in ATM by integrating traditional ATC with emerging UTM and Urban Air Mobility (UAM) systems. This integrated framework envisions an airspace where manned and unmanned aircraft operate cohesively. An important step in such environments is the concept of multi-link [7]. Such a network is based on a multi-layered approach, ranging from interconnected satellite constellations to ground nodes to relay data to users such as Airline Operational Control (AOC) and ATC to not only meet the increasing demand for low-latency, high-bandwidth communication but also to pave the way for adaptive communication strategies that can handle the complex dynamics of contemporary flight operations as shown in Figure 1. Future airborne systems are expected

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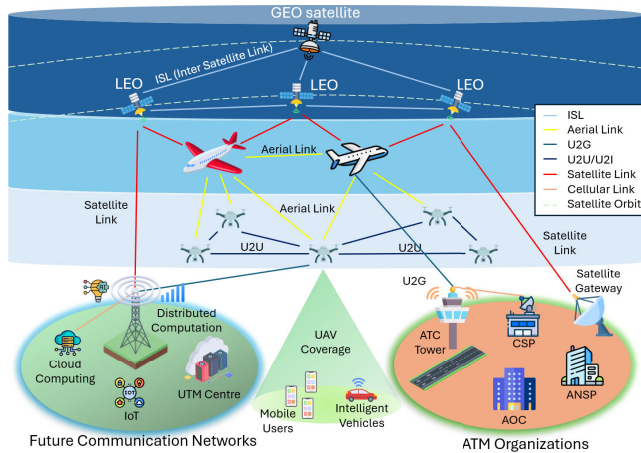


FIGURE 1. Future interconnected layered network for aeronautical communication.

to exchange significantly larger volumes of information with Air Traffic Control (ATC) and AOC via ground stations [8], satellites, and other aircraft, using a more secure and faster communication framework based on IP and new generations of wireless technologies [9]. These evolutions place stringent demands on communication availability, Quality of Service (QoS), and interoperability across multiple radio links. Therefore, achieving such high-speed, high-traffic connectivity remains a significant challenge not only for ground systems but especially in dynamic flight scenarios. The International Air Transport Association (IATA) predicts that by 2035, the connectivity used for ATS and AOC will need to transform dramatically [10], [11]. Modern RF engineering techniques and technologies will be integrated to not only boost performance but also to meet goals like improving flight safety, making airspace more efficient, and reducing the environmental impact of aviation. This study presents a forward-looking vision for the communications part (the ‘C’ in Communication, Navigation and Surveillance (CNS)). Rather than being limited by older, legacy systems, this evolution embraces innovative, non-traditional avionics solutions that promise significant benefits at costs and within time frames that airlines can realistically accept [12]. At present, establishing and maintaining radio links for airborne communications is often reliant on interrogation procedures (polling or scanning for a suitable frequency), which may lead to periods of unavailability. Future Air Navigation System (FANS) will demand increased data requirements for ATM; therefore, such interruptions or high-latency events will be less tolerable. The concept of multi-link arises in the aviation sector and may represent the next step in aeronautical communication.

This paper presents a comprehensive review of the current technology used in aeronautical communication, a discussion of several state-of-the-art systems, followed by a dense literature review on multi-link algorithms that could be used in aeronautical communication for intelligent link selection. By highlighting the shortcomings of existing

approaches—particularly their lack of integrated modeling for flight attitudes and obstructions caused by the aircraft’s own structure—and discussing how new techniques in machine learning and predictive decision-making could be leveraged to orchestrate link selection among terrestrial and satellite systems. By synthesizing results from various research domains, our work lays a foundation for novel decision-making algorithms capable of ensuring connectivity, even in the face of complex flight maneuvers.

A. RESEARCH MOTIVATION

Future Aeronautical Telecommunication Network (ATN) over Internet Protocol Suite (IPS) framework is poised to deliver unprecedented amounts of data across a myriad of communication links [9], necessitating uninterrupted connectivity during flight. However, several gaps remain unaddressed in current research and system designs. These include the need for resilient link transitions in environments where rapid data exchange is paramount, the lack of consideration for airframe shadowing effects as a decisive factor in link selection, and the potential to leverage pre-programmed flight routes from the Flight Management System (FMS) for predictive link optimization. Studies that explore multi-link systems for aviation either focus on link-level optimizations or ground network coverage. In 2017, National Aeronautics and Space Administration (NASA) analyses the interruptions of L-band/C-band links caused by airframe shadowing [13], but the challenge of simultaneously incorporating the influence of aircraft maneuvers, flight-path geometry, and the resulting shadowing effects into the link-selection decision process was not yet tackled. As a result, there is a pressing need for an integrated approach that models flight dynamics, airframe geometry, and advanced radio link technologies, part of Terrestrial Networks (TN) and Non-Terrestrial Networks (NTN), to ensure consistent data transfer under a variety of operational conditions. Specifically, our research is motivated by the following gaps:

- **Airborne Orchestrator:** Next-generation ATN/IPS network and its subsystems will require significantly more data traffic, making uninterrupted, and secure link contract establishments between airborne systems and different operators. Numerous types of data would be transmitted via new/improved communication channels. For improved safety, such data transmission shall remain uninterrupted in any environment and in any flight maneuver. Therefore, an orchestrator onboard the aircraft is assumed to conduct dynamic link selection based on decision making considering different factors from take-off phase to landing. This orchestrator can be part of the management function within the ATN/IPS framework and could be installed withing aircraft’s avionics.
- **Airframe Shadowing:** Airframe shadowing occurs when the aircraft’s own structure obstructs signal RF propagation. This phenomena could have great impact

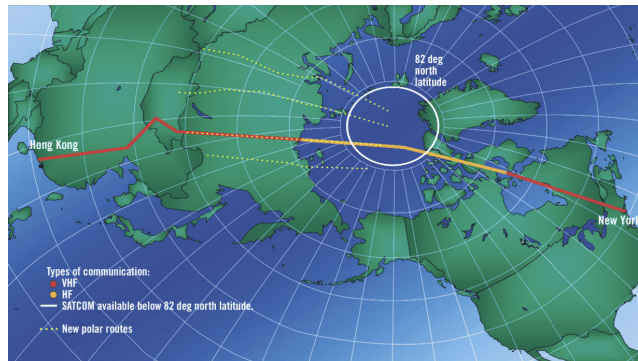


FIGURE 2. Polar region communication coverage [14].

on seamless data exchange in mid-flight. Flight routes that have steep descend paths or high rolls such as Local Terminal Control (LTC) could be impacted when using Very High Frequency (VHF) Data Link Mode 2 (VDL-M2) or SATCOM and maneuvers in proximity of Oceanic/Arctic Flight Information Region (FIR) boundary area where last resort is High-Frequency Data Link (HFDL) could also affect communication as seen in Figure 2. Moreover, unforeseen ATC instructions to alter the flight route or Traffic-Collision Avoidance System (TCAS) triggers for collision avoidance can introduce abrupt changes in the aircraft's attitude, further increasing the likelihood of signal obstruction. These dynamic conditions necessitate adaptive communication strategies.

- **Predictive Data Link Utilization:** In addition to instantaneous link selection, next-generation communication systems must incorporate predictive analytics to preemptively manage connectivity challenges. By integrating pre-flight route information from the FMS with real-time coverage maps and dynamic network performance data, the system can forecast potential disruptions.

B. CONTRIBUTIONS

This paper makes several key contributions to the research community in the domain of aircraft communication systems:

- Provides a thorough review of current technologies with a focus on the legacy ATN over Open Systems Interconnection (OSI) framework and modern data link technologies, detailing how communication links are established between aircraft and various users. This includes Air-to-Satellite (A2SAT) and Air-to-Ground (A2G). By collating and synthesizing findings from standards and regulations, the study offers a comprehensive overview of existing systems and highlights the methods used for link establishment and management.
- Underline the challenges inherent in the current link establishment approach, particularly those associated with interrogation link selection. In FANS this can lead to intermittent connectivity and high latency. This research also considers industry's need for a

multi-link strategy and the development of an intelligent decision-making algorithm that optimally selects communication links. Such an algorithm would incorporate flight dynamics and flight path information along other QoS/ Link Budget Analysis (LBA) parameters to predict and preemptively manage dynamic link transitions.

- Presents future trends based on an extensive literature analysis, indicating a clear shift toward integrated and adaptive communication systems by exploring the concept of an onboard orchestrator based on decision support systems leveraging Artificial Intelligence (AI) that would dynamically manage link selection among TNs and NTNs. This orchestrator would utilize pre-programmed flight routes from the FMS combined with real-time network performance data to achieve predictive link optimization.
- Offers a standards and regulation perspective, analyzing how current regulatory frameworks shape technology adoption and guide the transition toward adaptive aircraft communication networks.

Through these contributions, this study lays a solid foundation for the development of next-generation intelligent communication systems in aviation, addressing current limitations and guiding future research.

C. ORGANIZATION

This paper's structure can be seen in Figure 3 starting with Section I that states the research motivation, summarizes the paper's contributions, and outlines its structure. Then Section II logs connectivity requirements, reviews existing aircraft communication systems, details current links and protocols, and critiques the ATN/OSI architecture, highlighting interrogation limitations. Section III introduces a methodological framework for future networks by examining future technologies proposals, and analyzes the shift from OSI to IP-centric ATN/IPS, emphasizing implications for an onboard orchestrator. Section IV presents empirical results by comparing decision-making algorithms under two flight scenarios and presents initial results to back up the findings. Section V distills key insights and research directions, and Section VI concludes with a summary.

II. STATE-OF-THE-ART REVIEW IN AERONAUTICAL COMMUNICATIONS

The quest for high-capacity and seamless aeronautical communications has accelerated considerably in the last decade, spurred by developments in data link technologies, expansion of satellite services, and the growing demands of modern ATM for continuous and reliable real-time data exchange [9], [15]. According to [16], "data link" is an umbrella term that covers various types of data link systems and their associated subnetworks. As illustrated in Figure 4, a typical data link system is comprised of multiple interconnected subnetworks. While all aircraft equipped with data link capabilities have access to VHF data links, additional

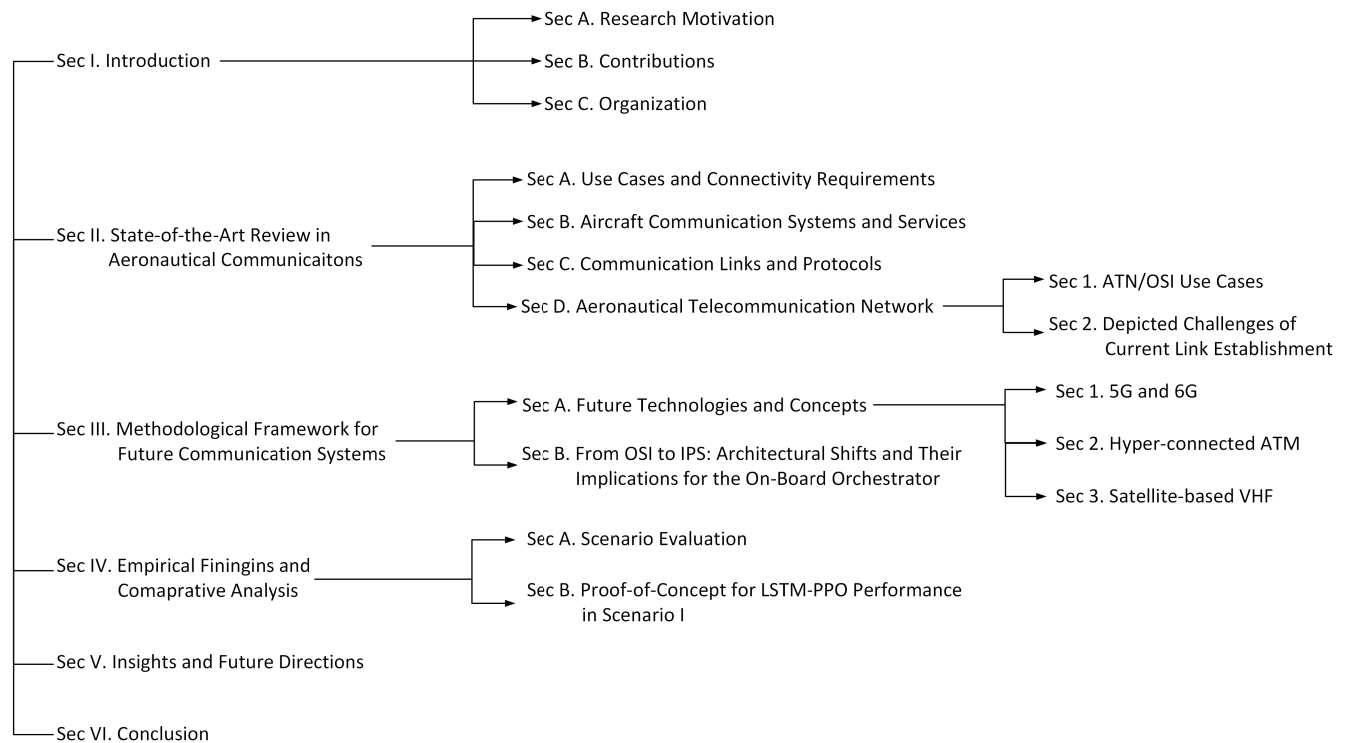


FIGURE 3. Survey structure chart.

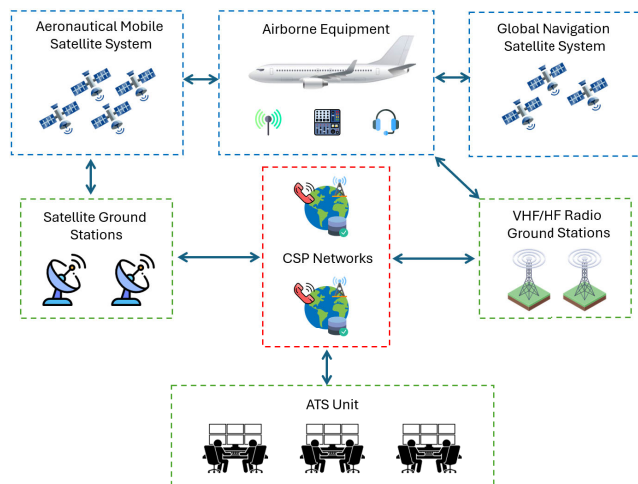


FIGURE 4. Overview of data link.

options (satellite, HF DL) are not universally available. Similarly, not all Communication Service Provider (CSP) offer High Frequency (HF) data link services, and some Air Navigation Service Providers (ANSPs) neither require nor permit the use of certain subnetworks (such as SATCOM) in their operational environments. First-generation datalinks such as Aircraft Communications Addressing and Reporting System (ACARS) and traditional digital voice communication such as VDL-M2 are gradually giving way to multi-link frameworks [17] that integrate high-speed A2G,

Air-to-Air (A2A), and A2SAT communication pathways. With the emergence of Fifth-Generation Mobile Network (5G) and numerous research on future Sixth-Generation Mobile Network (6G) networks, Low Earth Orbit (LEO) constellations, and advanced protocols that could be integrated in ATN/IPS, the technical horizons for aviation connectivity have expanded further [18], [19].

Despite this progress, the challenge to ensure consistent connectivity across different flight phases and environments remains. Aircraft in busy continental airspace have different Required Communication Performance (RCP) [20] than ones in Oceanic, Remote & Polar (ORP) regions. Even as bandwidth options increase, the fluctuation of link availability is impacted and shaped by factors including ground station density, satellite coverage geometry, and the real-time dynamics of flight maneuvers [21], [22]. Moreover, new ATM applications like four-dimensional (4D) Trajectory Based Operations (TBO) [23] and real-time in-flight data sharing through the concept of ‘aircraft as a sensor’ [24], place additional strain on existing communication infrastructures [25].

This section provides an overview of various aeronautical communication technologies, beginning with use cases and connectivity requirements across A2G, A2A, and A2SAT links in different environments. Aircraft communication systems and services are then examined with a focus on current technologies used for data transmission through channels. Communication links and protocols are analyzed

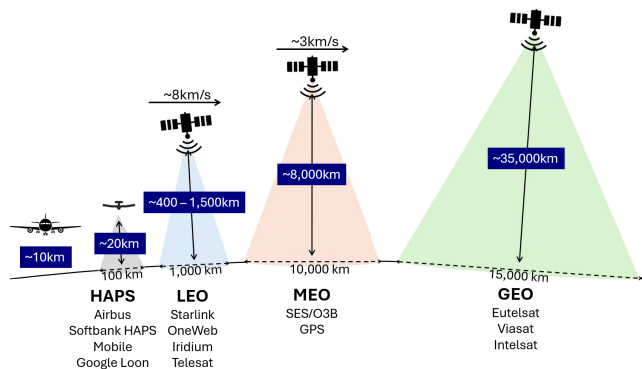


FIGURE 5. Representative altitudes and coverage ranges of haps and satellite constellations for aeronautical communications.

next, followed by a discussion on the currently used ATN/OSI architecture, current link selection processes and contract establishment, followed by challenges associated with future technology integration.

A. USE CASES AND CONNECTIVITY REQUIREMENTS

Data transfer from an aircraft happens through three main channels: air-to-ground for communication with terrestrial networks, air-to-air for direct exchanges between aircraft, and air-to-satellite for connectivity via space systems.

- Air-to-Sat Communication:** Air-to-satellite communication refers to the use of satellites as relay stations to connect aircraft with ground networks. In aeronautical communications, A2SAT links complement or replace traditional line-of-sight VHF radio and ground stations, especially in areas where such coverage is unavailable. Modern airliners carry SATCOM equipment including high-power radios and often steerable beam antennas that support digital data links for messaging and the internet. Usually, aircraft rely on Geostationary Earth Orbit (GEO) constellations (35,000 km) for SATCOM and Medium Earth Orbit (MEO) for positioning, but the rapid expansion of LEO could provide high throughput and low latency for safety-related traffic and for cabin entertainment. Figure 5 shows the different constellation altitudes and examples while also considering High Altitude Platform Systems that are used in specific missions to extend connectivity in remote regions, enhance network resilience, or serve as temporary communication relays during emergencies or infrastructure outages. This concept is illustrated in Figure 6a, where a single satellite maintains concurrent links with multiple aircraft and a ground station.
- Air-to-Ground Communication:** In commercial aircraft, A2G seen in Figure 6b refers to the exchange of voice and data signals between the onboard avionics and ground stations, typically operating in VHF bands with DSBAM for the 118–137 MHz range [26]. While this route underpins routine ATS over continental airspaces, it can be severely limited in ORP regions due to non-existent or sparse ground infrastructure.

In such regions, the flight crew may manually switch communication paths from the aircraft's audio control panel or the Control Display Unit (CDU) to alternate data links, including potential satellite systems.

- Air-to-Air Communication:** Aircraft frequently act as a forward or relay node for another, enabling indirect data paths back to the ground. This arrangement becomes useful in coastal transition zones, where terrestrial coverage tapers off as an aircraft departs land or approaches from the ocean as represented in Figure 7. For general inter-aircraft exchanges, A2A commonly uses VHF mirroring the protocols of short-range air-to-ground links. Another usage of this is for flight-critical systems such as TCAS operating at 1030 MHz for interrogation and 1090 MHz [27] for reply signals, frequencies shared with Secondary Surveillance Radar (SSR) for ATC.

The current trend in aviation communications is centered on the Performance-Based Communication and Surveillance (PBCS) concept, which was standardized by the International Civil Aviation Organization (ICAO) in 2017 [20]. Within this framework, RCP forms one of the three essential components of ATM, alongside Required Navigation Performance (RNP)/Area Navigation (RNAV) [28] and Required Surveillance Performance (RSP). RCP establishes performance standards that ensure continuous and efficient communication by defining requirements for transaction time, continuity, availability, and integrity. Specifically, operational parameters for a complete communication transaction, with each RCP type denoted by a designator that reflects the RCP expiration time which is the maximum allowable time for a transaction before an alternative procedure must be initiated. RCP 10 (10 seconds) is used when immediate controller intervention is needed, such as in busy airspace with tight separation between aircraft. RCP 60 (60 seconds) supports routine air traffic communications, including Controller–Pilot Data Link Communications (CPDLC) messages in controlled airspace. RCP 120 (120 seconds) is meant for en-route operations where controller intervention is necessary but not urgent, such as in remote or oceanic regions. RCP 240 (240 s) serves as the standard communication method in procedural airspace so that controllers can intervene when needed while maintaining separation based on communication performance. RCP 400 (400 seconds) is primarily used for newer technologies such as satellite voice communications, particularly in procedural airspace, where aircraft report their positions at designated points or times. RCP 400 can also act as a backup alongside RCP 240 systems. A summary of values can be seen in Table 1 with RCP 240 and 400 updated based on the last ICAO releases.

Operations in ORP rely mostly on RCP 120/240 due to the low number of aircraft in the airspace. Therefore, ATC communication is not time-critical, and not many adjustments such as elevation change are necessary. The challenge arises at the transition zones between continental (high dense

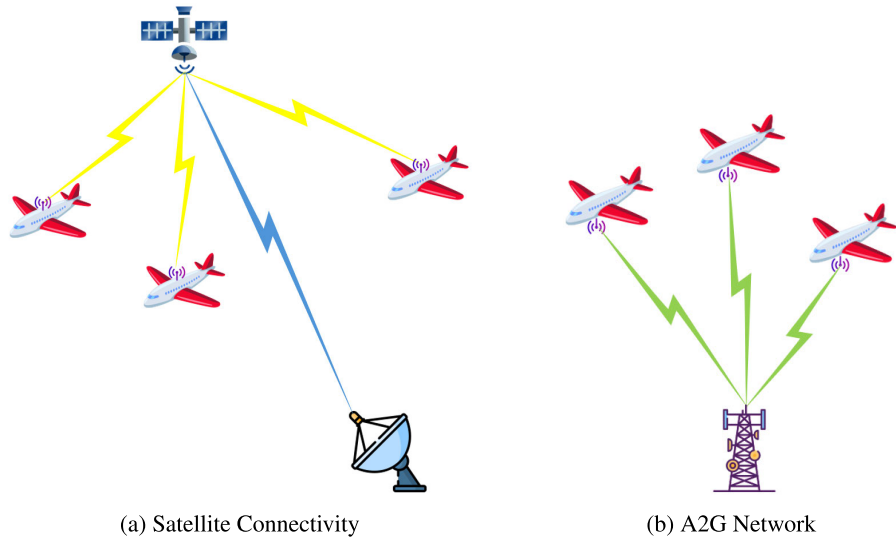


FIGURE 6. Aeronautical network types.

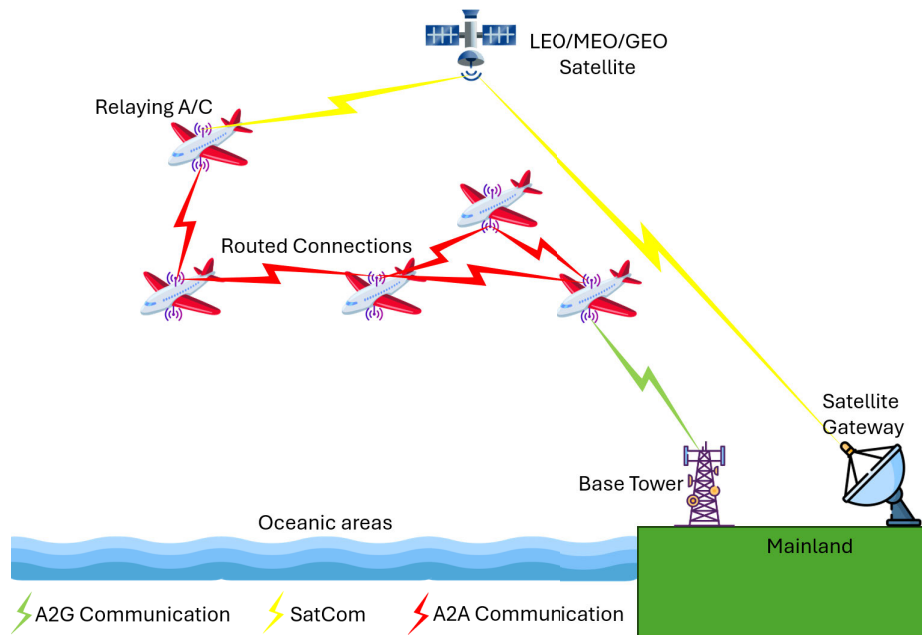


FIGURE 7. Hybrid communication integration.

TABLE 1. RCP values [20], [29].

RCP type	Transaction	Continuity	Availability	Integrity
RCP 10	10	0.995	0.99998	10^{-5}
RCP 60	60	0.99	0.9995	10^{-5}
RCP 120	120	0.99	0.9995	10^{-5}
RCP 240	240	0.999	0.9999	10^{-5}
RCP 400	400	0.999	0.999	10^{-5}

airspace) where VDL-M2 is predominantly used to ORP where SATCOM and/or HF is utilized. With the advent of advanced multi-link communication systems that integrate

satellite, HF, VHF, and possibly 5G/6G technologies, FANS must possess enhanced link management capabilities to dynamically adapt to variable flight conditions and environmental challenges. As these new technologies promise increased data throughput and more complex communication demands, it is imperative that existing frameworks such as PBCS be updated to reflect refined RCP parameters tailored for remote airspace operations.

B. AIRCRAFT COMMUNICATION SYSTEMS AND SERVICES
Aviation communication consists of two parts: onboard avionics and ground/air infrastructure. Onboard connectivity

and communication can be divided into cockpit and cabin traffic data. These systems span ground messaging networks, satellite links, onboard passenger connectivity, and even internal wireless sensor networks.

The Aeronautical Mobile Satellite Service (AMSS) is the system that allows aircraft to communicate with ATC and AOC via satellites when direct, line-of-sight radio signals aren't available [30]. Essentially, AMSS connects the aircraft's onboard communication systems to satellites orbiting Earth, which relay messages down to ground communication hubs. This system is vital for flights that travel long distances over oceans, polar regions, or other remote areas, ensuring pilots remain connected even when traditional radio methods can't reach. Inside the cockpit, AMSS is mainly used for essential safety communications and day-to-day operational exchanges. Pilots rely on it for satellite voice calls (SATVOICE), and to send and receive digital text messages via data link systems [31]. A common example is CPDLC, widely used during flights over the North Atlantic or Pacific. When a flight crosses these oceans, pilots and controllers use text messaging to exchange flight clearances, position reports, and other critical instructions. Since VHF radios have limited range, especially across large bodies of water, AMSS is used to bridge this gap by providing continuous communication via satellite relays. In fact, aviation regulations require aircraft operating beyond the range of standard VHF radio coverage to have alternative long-range communication capabilities. Typically, this means having at least one high-frequency (HF) radio and SATCOM system onboard to guarantee constant contact. That's why almost all aircraft models operating on long-haul international routes such as Boeing 777 or Airbus A350, carry an AMSS system from providers such as Inmarsat or Iridium, which also enable automatic position reporting known as Automatic Dependent Surveillance-Contract (ADS-C).

Below are the characteristics of each satellite constellation used to support AMSS:

- Iridium NEXT gives full global coverage—even over the poles. It runs on the L-band (1 GHz - 2 GHz) and supports SATVOICE, CPDLC, and ADS-C under FANS 1/A as depicted in Figure 8. Since the satellites are much closer to Earth (around 780 km up), the system has very low latency (10 ms) [16], [33], which makes communication feel almost instant. The main leverage of this constellation is that the orbits converge at poles having 66 active satellites, it's ideal for long-haul flights over oceans or polar regions where ground radio doesn't reach;
- Inmarsat I-4 uses GEO satellites which covers most of the globe, except the poles, and also runs on L-band. Inmarsat supports services like SATVOICE, CPDLC, and ADS-C, mainly through its Classic Aero and newer SwiftBroadband (SBB) safety services. Latency is a bit higher (250 ms) due to the higher orbit, but it's still reliable for regulated cockpit comms [16], [34]. It's commonly used by aircraft flying over oceans;

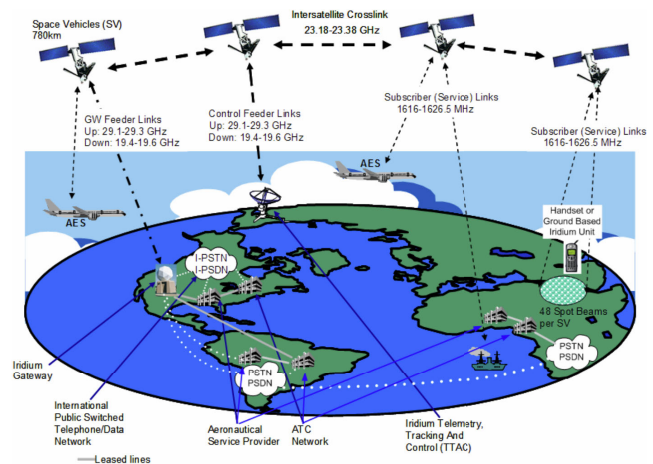


FIGURE 8. IRIDIUM AMSS [32].

- Global Positioning System (GPS) is the U.S. satellite navigation system, and it's been the backbone of aviation positioning for decades. With around 30 satellites in MEO, it provides accurate global positioning that supports everything from en-route navigation to approaches. It's also a key input for Automatic Dependent Surveillance-Broadcast (ADS-B). GPS operates in L1 (1575.42 MHz) and L5 (1176.45 MHz) bands for civil aviation users. It is approved under ICAO standards for primary means navigation when supported by onboard integrity monitoring systems like Receiver Autonomous Integrity Monitoring (RAIM) or Satellite-Based Augmentation System (SBAS) [26], [35].
- Galileo is Europe's answer to GPS [36], offering high precision navigation with growing global coverage. It works on dual frequencies, which means better accuracy and reliability throughout environments. When used together with GPS (which most modern receivers do), it improves performance for PBN and other advanced procedures. Galileo is interoperable with GPS and often used in a multi-Global Navigation Satellite System (GNSS) receiver to enhance availability and accuracy in aviation. The inclusion of Galileo improves RAIM performance and is expected to play a vital role in future PBN environments [37].

In-Flight Entertainment and Connectivity (IFEC) refers to the onboard systems that offer entertainment content and internet connectivity to both passengers and crew members during a flight. Unlike operational services such as ATS Message Handling Services (AMHS) and AMSS, which focus on safety and flight-critical communications, IFEC caters primarily to passengers, enhancing their onboard experience. It includes traditional entertainment options like seatback screens and audio/video-on-demand services, as well as modern connectivity features—such as onboard Wireless Fidelity (Wi-Fi), live television, voice and messaging over internet protocols, and streaming media. Nowadays, IFEC

systems have shifted from being seen as a luxury item to an expected standard for passengers. These advanced systems depend on robust satellite or air-to-ground (ATG) connections to deliver high-speed internet into the aircraft cabin. Satellite IFEC solutions utilize broadband connectivity provided by satellites operating in the Ku-band or Ka-band, delivered by companies such as Inmarsat GX [38], Viasat [39], Intelsat [40], or new low-Earth orbit constellations like Starlink and OneWeb. These satellite services can deliver multi-Mbps data speeds, allowing passengers to browse the internet, send emails, use Virtual Private Networks (VPNs), or stream videos even on flights crossing oceans or remote regions [41]. Over certain land regions, such as within the United States, airlines often use air-to-ground networks that connect aircraft to the internet via cellular towers—providers such as Gogo offer this type of service. Besides enhancing passenger experiences, IFEC connectivity also delivers important operational benefits for airlines. The cabin’s data link can serve as an additional resource for cockpit and crew, enabling secure access to real-time weather updates or even telemedicine consultations in the event of a medical situation onboard. Airlines also increasingly leverage IFEC connectivity to improve aircraft maintenance and operational efficiency. For instance, aircraft health monitoring data can be transmitted in real-time during flight, and software updates for critical onboard systems can be sent mid-flight rather than waiting until the aircraft is on the ground. According to industry studies [42], [43], enhanced IFEC connectivity enables more dependable real-time data sharing between aircraft and ground facilities, ultimately contributing to improved safety, optimized flight routing, and lower maintenance costs.

Next generation air navigation services are called FANS. FANS is fundamentally a communication and surveillance system defined by ICAO [16], primarily CPDLC and ADS-C. It facilitates the inclusion of data link communications over Satcom or VHF/VDL-M2. There are 5 different FANS systems which are described in Table 2, listed in evolution order.

C. COMMUNICATION LINKS AND PROTOCOLS

The Single European Sky ATM Research (SESAR) programme, managed by the SESAR Joint Undertaking (SESAR JU), is working to develop the European Air Traffic Management Architecture (EATMA) [44]. A key aspect of this evolution is the transition of cockpit communications from voice to data systems, with the goal of improving both communication efficiency and overall flight safety. Aviation has evolved during the past decade with communication link technologies like AeroMACS and L-band Digital Aeronautical Communications System (LDACS) being more promising and expected to deliver more reliability, but also support higher data transfer, part of the multilink concept [45]. The transition to LDACS and AeroMACS will happen gradually, with initial usage working along VDL-M2 and SATCOM. Below are all links explained in detail:

TABLE 2. Comparison of FANS and ATN communication systems.

System	Features Included	Primary Usage	Example Use Case
FANS 1/A	ATS Facilities Notification (AFN), CPDLC, ADS-C via ACARS; supports RNAV & RNP	Oceanic and remote-area routes	Pacific oceanic routes
FANS 1/A+	All FANS 1/A features plus message latency monitoring	Oceanic routes requiring strict communication quality	Transatlantic routes
FANS 1/A ADS-C	AFN, ADS-C via ACARS; excludes CPDLC	Surveillance without digital communication	Cargo operations over oceanic airspace
ATN B1	Context Management (CM), CPDLC (via ATN)	ATC clearances and communications in European airspace	Commercial flights within European upper airspace
FANS 1/A – ATN B1	Compatible with both FANS 1/A and ATN B1 (CM, CPDLC, ADS-C via ACARS & ATN)	Seamless CPDLC across diverse global airspaces	Flights from North America to Europe

- LDACS is a next-generation terrestrial datalink developed under SESAR project PJ14 [46] operating in the L-band, LDACS offers wideband communication with excellent propagation for currently only air-ground data exchange. Designed to complement VDL2, it supports demanding future services, including Alternative Positioning, Navigation, and Timing (APNT), surveillance, and Remotely Piloted Aircraft System (RPAS) Command and Control (C2). Technically, LDACS uses a 4G-like architecture with Orthogonal Frequency-Division Multiplexing (OFDM) modulation and advanced protocols. Technically, LDACS is a broadband OFDM system operating in the 960–1164 MHz L-band for air-ground (A/G) communications, offering up to 200 NM coverage. It uses a 498 kHz occupied channel bandwidth (50 active sub-carriers) in an Frequency-Division Duplex (FDD) scheme, with forward link in 1110–1156 MHz and Reinforcement Learning (RL) in 964–1010 MHz, and a 146 MHz duplex spacing. Each 240 ms super-frame comprises broadcast, multi-frame, and random access segments. Ground transmitters can provide up to 44 dBm Equivalent Isotropic Radiated Power (EIRP) with ≤ 11 dB Peak-to-Average Power Ratio (PAPR) and spurious emissions below -36 dBm. The ground receiver achieves a reference Bit-Error Rate (BER) of 10^{-6} , with sensitivities ranging from -103 dBm (Quadrature Phase-Shift Keying (QPSK) $\frac{1}{2}$) to -88 dBm (64 Quadrature Amplitude Modulation (QAM) $\frac{3}{4}$). Timing accuracy is within $\pm \frac{1}{11}$ of the cyclic prefix, and

TABLE 3. LDACS characteristics [46].

Parameter	Specification
Polarization	Vertical
Designed Coverage	Up to 200 NM
Frequency Range	960–1164 MHz
Forward Link	1110–1156 MHz
Reverse Link	964–1010 MHz
Occupied Bandwidth	498.05 kHz (50 sub-carriers + unmodulated DC)
Channel Grid	0.5 MHz spacing (center frequencies on multiples of 0.5 MHz)
Duplex Spacing	146 MHz
Co-Channel Interference Rejection	≥ 14 dB (design target)
Max Coverage Range	200 NM (limited by guard times and interference design)

**FIGURE 9.** Network speed comparison [50].

frequency precision is better than ± 0.1 ppm. Table 3 provides a complete list of LDACS characteristics along with specific values.

- AeroMACS is a broadband wireless datalink specifically designed to handle the growing demand for data-intensive applications at airports [47]. AeroMACS is based on IEEE 802.16e Worldwide Interoperability for Microwave Access (WiMAX) [48] standard for high-capacity communications on airport surfaces [49]. Comparing AeroMACS with other ground wireless technologies, it sits above in terms of network speed as seen in Figure 9. It supports both mobile endpoints (aircraft, vehicles, and handheld devices) and fixed infrastructure (airport sensors). Nowadays, AeroMACS is used only on certain airports such as Lisbon and some in China, but not to its full potential. As aircraft could store various data while flying, AeroMACS can act as a fast method to “download” information while the aircraft is on ground, or taxiing. Technically, AeroMACS equipment can operate across multiple channel assignments spanning the 5000–5150 MHz

TABLE 4. Technical characteristics of AeroMACS [51].

Technical Parameter	Specification
Frequency Range	5 000–5 150 MHz (primary aeronautical C-band allocation; 5 091–5 150 MHz internationally)
Channel Bandwidth	5 MHz
Channel Spacing	250 kHz increments for center frequencies
Waveform & Duplex	Orthogonal FDMA (OFDMA), Time-Division Duplex (TDD) (IEEE 802.16e)
Modulation	Adaptive up to 64-QAM
Data Throughput	Up to ~ 7 Mbps downlink / ~ 5 Mbps uplink per channel (under favorable conditions)
Security	PKI certificates, Extensible Authentication Protocol (EAP)/Transport Layer Security (TLS) authentication, AES encryption
QoS & Scheduling	Supports Extended Real-Time Polling Service (ertPS), Real-Time Polling Service (rtPS), Non-Real-Time Polling Service (nrtPS), Best-Effort (BE); priority flow management

range, following a profile that includes 5 MHz-wide contiguous channels. Each base station manages a sector or cell, using adaptive modulation and coding. The system implements Internet Protocol version 4/6 (IPv4/IPv6) support with mandatory dual-stack or tunneling for backward compatibility, while mobility is managed through standardized ATN/IPS frameworks such as those described in [9]. AeroMACS employs its own Public Key Infrastructure (PKI) for device authentication and key management, with certificate lifetimes typically aligned to maintenance cycles (five years). The characteristics of AeroMACS are condensed in Table 4.

- VDL-M2 [52] is a modern VHF data link system designed to replace the aging, low-speed ACARS designed in 1978. Unlike ACARS’ 7-bit character-oriented approach, VDL-M2 is bit-oriented and supports higher bandwidth data applications. VDL-M2 is a data-only service operating within the 117.975–137 MHz VHF band and can provide transparent, code-independent data transport and serves as a subnetwork for the ATN. The Common Signalling Channel (CSC) at 136.975 MHz is reserved for Mode 2 control and signaling across all countries. It operates on a physical layer using differential 8-phase modulation (D8PSK) at 10.5 ksymbols/second (yielding 31.5 kbps) with bit interleaving and scrambling. The data link layer consists of two parts: a Medium Access Control (MAC) sublayer that employs Carrier Sense Multiple Access (CSMA) for collision sensing, and an Aeronautical VHF Link Control (AVLC) sublayer using an High-Level Data Link Control (HDLC) similar protocol for error

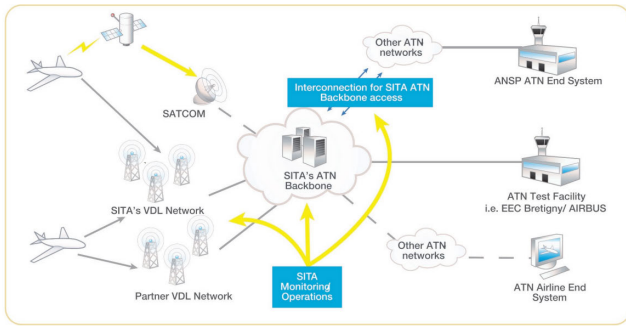


FIGURE 10. SITA's ATN/VDL-M2 service by Eurocontrol [54].

detection, sequencing, and addressing. Partial network layer functionality is provided via International Organization for Standardization (ISO) 8208 protocols [53], integrating onboard VDL-M2 stations as nodes within the ATN. Figure 10 shows the integration of VDL-M2 over ATN by SITA. VDL-M2 was deployed by Aeronautical Radio, Inc. (ARINC) and SITA already in use on over 2500 aircraft worldwide according to [54].

- CPDLC is a two-way data link system engineered to supplement traditional voice communications in ATC by providing structured, non-time-critical message exchanges between controllers and pilots [16], [55]. Services offered under CPDLC include Data Link Initiation Capability (DLIC) for establishing connectivity, ATC Communications Management (ACM) for automating message flow, ATC Clearances (ACL) for issuing operational directives, and ATC Microphone Check (AMC) to verify channel integrity. Currently, aircraft flying as General Air Traffic (GAT) above FL285 within the SES airspace of the EUR region must be equipped with CPDLC as per [56].
- High Frequency Data Link (HF DL) [57], [58] is an advanced digital communication system tailored specifically for the ATN. It offers a cost-effective alternative to traditional HF voice and SATCOM systems. Built upon the standards defined in MIL-STD-188-110A [59], the HF DL integrates aircraft subsystems, including HF data units, modulation and demodulation capabilities, and specialized control interfaces, alongside a network of ground stations equipped with high-power transmitters, shared antennas, and dedicated HF modems. Technically, according to [60], HF DL system employs Time Division Multiple Access (TDMA) technique, using periodic transmissions known as “squitters” every 32 seconds. These squitters are used in precise synchronization of network timing, frequency management, and dynamic allocation of communication slots. The system is versatile, capable of handling data transmission rates ranging from 300 to 1,800 bits per second, adapting effectively to varying operational requirements and environmental conditions. This system is designed specifically for the challenges of long-range HF data communication in ORP areas [61]. The way

this works is the protocol divides larger High Frequency Network Protocol Data Units (HFNPDU) into more manageable Basic Data Units (BDUs), each with an 8-bit header for identification and tracking. These BDUs are transmitted using numbered data Link Protocol Data Units (LPDUs), which utilize uplink and downlink sequence numbers managed via modulo 32 arithmetic. Acknowledgments within the system are streamlined through concise 8-bit vectors known as U(A)vect and D(A)vect, efficiently indicating the successful receipt or Negative ACKnowledgment (NACK) of up to eight consecutive packets. To mitigate the unpredictable nature of HF propagation, HF DL continually monitors frequencies and adjusts dynamically through real-time synchronization provided by the recurring squitters. Precise timer settings, such as a 180-second timer for connection establishment (tN1) and a 60-second timer for flow control management (tN7), are meticulously maintained, ensuring efficient management of logical channels and timely retransmission of data packets.

D. AERONAUTICAL TELECOMMUNICATION NETWORK (ATN)

ATN is a globally standardized communication framework defined by ICAO [62] for secure data and voice information exchange between aircraft and ground systems. The primary use case of this system is to support communication for ATC, AOC, and ATS. ATN is a major network that integrates numerous sub-networks; therefore, it can be considered a network of sub-networks. To easily represent the applications and all the subnetworks of ATN, Figure 11 was created. From the data traffic perspective, ATN facilitates safety-critical services and operational communication. The safety-critical services are communication between aircraft and ATC for clearance, instructions, and advisories. These communications are prioritized based on QoS [63]. The current network has an OSI model (ATN/OSI) based on standardized ISO protocols. The core protocol stack includes the Connectionless Network Protocol (CLNP) defined in ISO/IEC 8473 [64], the Transport Protocol Class 4 (TP4) specified in ISO/IEC 8073 [65], and the Interdomain Routing Protocol (IDRP), based on ISO/IEC 10747 [66], which supports dynamic routing between different routing domains.

1) ATN/OSI ARCHITECTURE

The ATN/OSI architecture is structured around a five-layer model that consolidates certain traditional OSI layers to meet the operational and certification requirements of aeronautical communication. The OSI model has 7 layers as listed in Table 5, but ICAO defined ATN/OSI of only 5 layers, merging session, presentation, and application layers under the application layer name. This optimized layering adapts the general OSI principles to the specific needs of the CNS/ATM system originally defined in [67], with the latest

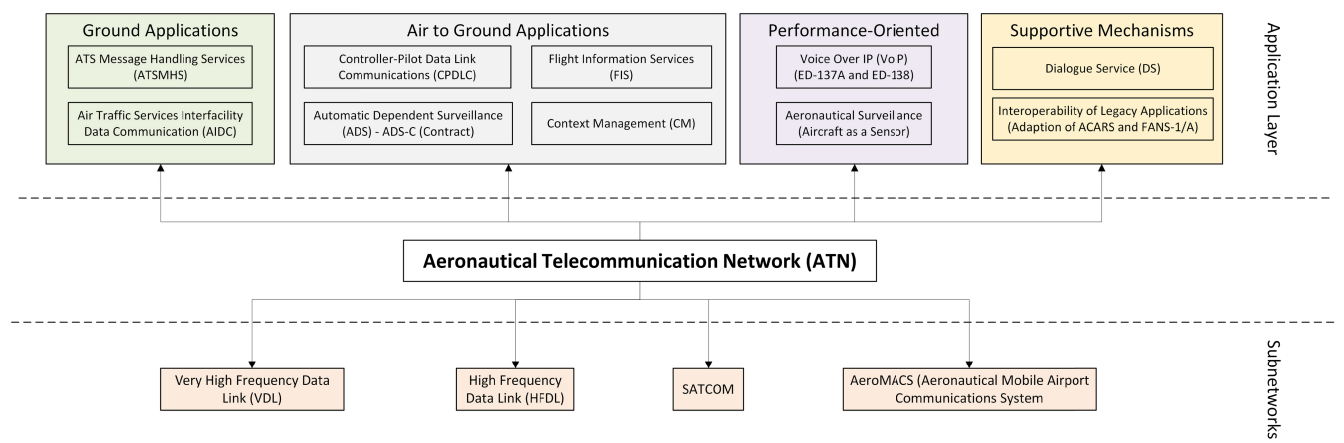


FIGURE 11. Aeronautical telecommunication network applications and subnetworks.

TABLE 5. Layered architecture of OSI model, ATN/OSI having layers 5-7 merged under a single layer: application layer.

Layer	Name	Data Packag- ing	Function
7	Application	Data	High-level APIs, including resource sharing, remote file access
6	Presentation	Data	Translation of data between a net- working service and an applica- tion; including character encod- ing, data compression and encryp- tion/decryption
5	Session	Data	Managing communication ses- sions, continuous exchange of in- formation in the form of multiple back-and-forth transmissions be- tween two nodes
4	Transport	Segment	Reliable transmission of data seg- ments between points on a net- work, including segmentation, ac- knowledgement and multiplexing
3	Network	Packet	Structuring and managing a multi-node network, including addressing, routing and traffic control
2	Data-link	Frame	Reliable transmission of data frames between two nodes con- nected by a physical layer
1	Physical	Bit/Symbol	Transmission and reception of raw bit streams over a physical medium

updates in [25]. It has to be mentioned that the OSI model and its associated standards have never been fully implemented in any domain [68].

At the lowest level, the Physical Layer is responsible for the transmission of raw bits over radio frequency or satellite communication mediums. Currently used communication means are VDL-M2, HF DL, SATCOM, AMSS, and Mode S datalinks. For VDL Mode 2 specifically, the infrastructure includes a network of VHF Ground Stations (VGSs) interconnected via OSI-compliant routers. Depending on the position



FIGURE 12. ATN/OSI interaction scheme.

on the globe, the airborne system may use different links depending on availability and connection requirements which are described in sub-section II-D2. Above the physical layer is the Data Link Layer. Its purpose is to maintain node-to-node communication by framing and error checking. Each air-ground or ground-ground connection relies on specific MAC-level protocols defined by the subnetwork types for data integrity across noisy or variable-quality channels. Next is the Network Layer with CLNP for packet forwarding across a network of subnetworks. Routing between domains is dynamically managed through the IDRP, allowing aircraft to maintain network connectivity during flight across national and service-provider boundaries. Also part of the network layer is the Sub-network-Dependent Convergence Function (SND CF) that is used for adapting the network layer protocols to different lower-layer technologies. Then, the transport layer provides end-to-end delivery using TP4 which is a protocol used for connection-oriented and fragmented data units. Connection management is achieved via the interaction scheme for transport communication that follows a sequence of connection setup, data/acknowledgment exchanges, and tear down as shown in Figure 12. The last layer, the application layer [18], combines CPDLC, ADS-C, Flight Information Services (FIS), AMHS, and ATS Interfacility Data Communication (AIDC). These applications are implemented over the Upper Layer Communication Service (ULCS) and rely on secure transport and networking mechanisms as outlined in [62]. Furthermore, ATN/OSI is

designed for security services through mechanisms aligned with ISO/IEC 7498-2 [69] and ISO/IEC 10181-x [70] standards for cryptographic authentication and validation within the protocol stack.

2) DEPICTED CHALLENGES OF CURRENT LINK ESTABLISHMENT

In the current ATN/OSI architecture, the establishment of communication between an aircraft and a ground system follows a multi-layered connection setup sequence. Using VDL Mode 2 (VDL-M2) as an example, the path from aircraft to user involves several stages across the protocol stack. Initially, at the physical and link layers, the aircraft establishes a connection with a ground station via VHF radio MAC procedures. Here, interrogation mechanisms allow ground stations to periodically request identification and link quality information from aircraft, to determine link availability. If successful, a MAC association is formed. At the network layer, an X.25 Switched Virtual Circuit (SVC) [71], [72] is established which one calls a “link”. The link maintains a virtual network path created between the aircraft and the ground routers. This circuit setup introduces overhead due to signaling exchanges such as Call Request, Call Accepted, and Clear Request. Although overhead is mitigated through piggybacking acknowledgments [73], segmentation optimization (window mechanisms), and HDLC usage [9], future airborne communication systems could leverage predictive mobility management, intelligent link orchestration, and dynamic congestion-aware routing to further minimize latency, reduce retransmission cycles, and support resilient communication even under high-load or degraded link conditions. At the transport layer, error correction, retransmission mechanisms, and flow control are managed. Finally, at the application layer, the CM application is activated. The aircraft executes a CM Logon to register itself with the ATN ground system, allowing services like CPDLC and ADS-C to become operational. Once the CM service is completed successfully, AOC and ATC applications can interact with the airborne end system through ground communication servers. This model is based on link interrogation and static priority assignment: available communication links (VDL-M2, SATCOM, HFDL) are ordered according to a predefined priority list. The system selects the highest-priority link that is available, without regard to future trajectory, signal dynamics, or operational context. While effective for traditional low-data-rate applications, several challenges arise when considering future airspace operations that demand higher data throughput, dynamic service continuity, and predictive mobility support:

- **1.** The interrogation link establishment is inherently reactive and lacks dynamic adaptability. Current procedures only detect and act on link degradation or failure after the event occurs. In operational environments characterized by high mobility (fast-moving aircraft) or coverage boundaries (polar regions, oceanic airspace), this can result in service interruptions or degraded

performance, which are unacceptable for emerging real-time services like dynamic 4D trajectory updates.

- **2.** The system is built around a static link prioritization model, which is increasingly inadequate in dynamic flight conditions. Aircraft maneuvering actions such as steep banking, rapid descents, or quick heading changes can substantially alter antenna orientations, propagation paths, and link qualities. In such scenarios, line-of-sight dependent VHF links like VDL-M2 are especially vulnerable to sudden degradation or complete interruption. Under the current architecture, link switching is reactive—it only occurs after signal deterioration has reached critical thresholds. This delay can cause temporary communication blackouts, session interruptions, or increased latency, particularly harmful for mission-critical operations like 4D trajectory management or emergency communications. There is no capability today to anticipate link performance degradation based on flight dynamics, weather influences, or predicted loss of coverage.
- **3.** There is no predictive link selection mechanism integrated into the CM service. Currently, the CM Logon service statically associates the aircraft with the “best available” link based purely on a predefined priority table without adapting dynamically to real-time context. Future airborne communication architectures require a smarter, orchestrated approach. One solution could be an intelligent orchestrator embedded within CM that leverages AI and real-time situational awareness to adjust link selection proactively.

Therefore, a dynamic and predictive system would continuously monitor both flight parameters (attitude, speed, altitude) and network metrics (signal strength trends, BER fluctuations) to proactively trigger a seamless transition to an alternative link before service degradation occurs. In the context of highly data-centric future operations, where safety margins depend on real-time data delivery, a predictive and anticipatory link management mechanism is essential to maintain operational integrity. Theoretically, CM could incorporate an intelligent orchestrator to dynamically influence CM logon behavior on link selection before it initiates the logon process. By evaluating predictive flight path information (upcoming terrain, projected entry into oceanic airspace), environmental conditions (storms, turbulence affecting signal propagation), aircraft dynamics (maneuvers leading to loss of link stability), and network status (congestion levels on VDL-M2 ground stations), the orchestrator could dynamically reprioritize available links. This need is particularly acute in operations across ORP regions where coverage is sparse and where relying on post-failure reactive switching could cause critical gaps in safety communications or IFEC. The use of such predictive orchestration would enable “make-before-break” link management to ensure a new link is fully established and stable before the current one deteriorates—a fact that would enable uninterrupted CPDLC sessions, ADS-C reports, and future

high-data applications like real-time engine monitoring, weather video relays, IFEC, or any other communication channel between A/C and ground.

That said, the evolution toward dynamic and predictive intelligent link management within the future ATN framework is not merely an optimization but a fundamental requirement to support scalable communication infrastructure envisioned for future global air communication systems.

III. METHODOLOGICAL FRAMEWORK FOR FUTURE COMMUNICATION SYSTEMS

This section presents a detailed description of the current ongoing trends, concepts, and technologies within the aviation communication field.

A. FUTURE TECHNOLOGIES AND CONCEPTS

1) 5G AND 6G

The integration of 5G and the upcoming 6G communication technologies marks a significant advancement in aviation communications, addressing rising demands for higher data rates and increased connectivity. The International Telecommunication Union (ITU) is in charge of managing spectrum allocations and setting harmonized global standards for smoother international adoption of these advanced systems. 5G could support aviation-critical applications such as augmented and virtual reality, Internet of Things (IoT), and safety-critical communication through enhanced Mobile BroadBand (eMBB), Ultra-Reliable Low-Latency Communication (URLLC), and massive Machine-Type Communication (mMTC). However, recent deployment of terrestrial 5G networks in the adjacent 3.4–4.0 GHz [74] (C-band) has raised substantial safety concerns due to potential interference with aviation radio altimeters operating at 4.2–4.4 GHz, increasing risks such as loss of situational awareness or Controlled Flight Into Terrain (CFIT) [75]. Radio Technical Commission for Aeronautics (RTCA) and European Organisation for Civil Aviation Equipment (EUROCAE) have collaboratively developed mitigation strategies to address these challenges. Some measures involve defined spectrum separation, transmission power limits, downward antenna tilting, and protective exclusion zones around airports. RTCA has also spearheaded extensive testing and continuously updates Minimum Operational Performance Standards (MOPS) for radio altimeters for avionics resilience against 5G interference. In 2020, they conducted a study on 5G C-band impact on low range radar operations [76] concluding that 5G telecommunications systems operating in the 3.7–3.98 GHz band pose a significant risk of harmful interference to radar altimeter applications which can be seen in Figure 13, with potential for catastrophic aviation safety impacts in the absence of appropriate mitigation measures. Some of the listed measures are implementing strategic placement and orientation of 5G base stations, including limiting Active Antenna System (AAS) vertical scan angles and optimizing deployment planning, designing

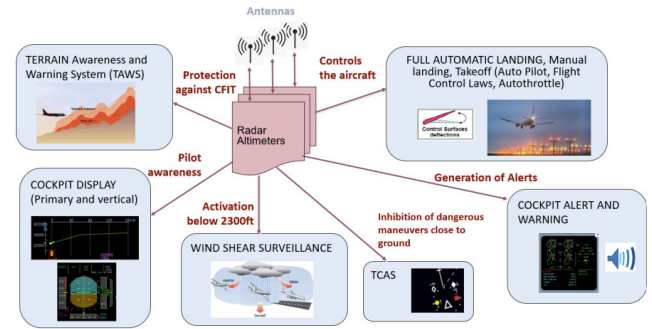


FIGURE 13. Radio altimeter applications [79].

antennas with reduced emissions in critical altitude bands, and developing and deploying radar altimeters with enhanced interference rejection capabilities, guided by revised MOPS currently being updated by RTCA SC-239/WG-119 [77], [78] planned to finish in 2027.

Despite the scepticism from the regulatory bodies, recent studies have published promising applications and results for 5G integration in aviation. References [80], [81], [82] investigated various dimensions of security and cyber-physical resilience in 5G-integrated networks, including AI-driven anomaly detection for aviation applications, digital twin technologies for safety, and deployment of embedded cyber-physical systems supported by 5G and C-V2X connectivity. 5G infrastructure and network design has been deeply analysed in [83], [84], [85], and [86] experiment with handover in UAV NTN ecosystem. These studies show that adding 5G to aviation could positively impact and extend current applications.

Looking ahead, the 6G standard, expected by 2030, will offer substantial improvements in bandwidth, latency, and reliability, enabling advanced scenarios such as integrated air-ground-space connectivity and autonomous system networks in a more secure and faster manner than 5G. 6G emphasizes sustainability and energy efficiency, while aligning with global environmental targets outlined in the UN Sustainable Development Goals (SDGs). The research community has a deep interest in 6G, thus NTN and UAM frameworks have been proposed in [87] and [88] for NTN and UAM, and a channel propagation study [89] now shows that practical GX-band air links incur 2–24 dB excess loss and sustain one-way latency of 0.12–0.14 s, confirming the technical viability of 6G NTN. One of the most important add-ons of 6G over 5G is digital twins and their use to benchmark AI algorithms on design-level network architectures. References [90], [91] have shown that coupling a physics-accurate twin with the learning agent can turn into quantifiable gains through cut-in-half tracking RMSE under 6 g turns and a 40% drop in end-to-end service delay for 20 simultaneous users. Although the initial implementation of 6G technology will be in ground telecommunications in specific regions, and most probably, static applications will be prioritized it's not too long until 6G could see the light of day in the aviation industry.

2) HYPER-CONNECTED ATM

One of the most promising aviation concepts is Hyper-connected ATM (HCATM) which is an architectural paradigm first proposed as a solution to Project 14, wave 2 of SESAR2020 (solution reference: Solution PJ.14-W2-61 [92]). This concept was later articulated by the International Coordinating Council of Aerospace Industries Associations (ICCAIA) and the Civil Air Navigation Services Organization (CANSO) at ICAO's Fourteenth Air Navigation Conference [93], and later formalized through ARINC Project Initiation/Modification (APIM) submission 10 [94]. It envisages an opportunistic overlay of commercial non-safety connectivity beneath the safety umbrella of protected VDL-M2 and L-band SATCOM. By intelligently routing safety-critical messages over the optimal path—commercial broadband when available, switching instantly to protected links upon degradation—airspace users and service providers can unleash vastly greater aggregate throughput, reduce latency, and achieve near-global reach without constructing wholly new safety radios or acquiring additional spectrum. Drawing upon the EU-US collaboration [95], SESAR's Future Communication Infrastructure (FCI) business case [96], and 3rd Generation Partnership Project (3GPP) standards for NTN [97], it demonstrates how a secure VPN overlay, continuous performance monitoring, and instantaneous switch-with-reversion logic can deliver the capacity and resilience essential for TBO and PBCS. HCATM serves as a software approach to VHF decongestion. As opposed to LDACS which has a similar scope to HCATM, the after-mentioned system does not require infrastructure deployment as it is mainly software. The HCATM conceptual framework integrates three principal functional layers: secure overlay channel, virtual overlay radio, switch-with-reversion logic. The secure overlay channel proposes a VPN tunnel established between a segregated aircraft avionics domain to a ground node of CSP. Although encapsulated within public Internet infrastructure, this overlay enforces military-grade confidentiality, integrity, and non-repudiation in accordance with ARINC 811 security guidance [98], [99] and ICAO's zero-trust recommendations [100]. The virtual overlay radio layer implies that continuous telemetry of link-layer Key Performance Indicators (KPIs) (throughput, latency, packet loss, bit error rate) is performed at millisecond granularity. Drawing on definitions from Release 17 NTN work items [97], the virtual radio entity assesses each commercial path against predefined service-level objectives. Therefore, when the thresholds are exceeded, automation triggering of real-time alerts occur, that facilitate migration to alternative routes. Historical performance could feed machine-learning predictors to optimize route selection and handover between terrestrial and non-terrestrial networks. At the last layer, the safety-critical message that could be CPDLC, ATS message, FANS-1/A, ATN B1/B2 is evaluated by a decision-engine that selects the ideal path based on real-time performance data. If the commercial link cannot guarantee RCP-130 for CPDLC

or encounters severe degradation, the message is atomically retransmitted over the protected VDL-M2 or SATCOM Performance Class B link. This logic ensures the “four nines” availability (99.99 %) mandated by ICAO PBCS requirements [20]. Figure 14 separates connectivity into Terrestrial Network (TN) with AeroMACS on the apron and VDL-M2/LDACS A2G sites along the route, all back-hauled by ATN/ System-Wide Information Management (SWIM) and an overlaying NTN. NTN extends coverage and bandwidth: GEO SATCOM safeguards CPDLC over oceans, HF DL supplies ionospheric redundancy, while LEO/ MEO constellations deliver low-latency 5G/6G throughput for both safety and cabin traffic [101]. Accordingly, the decision-engine or an onboard orchestrator must track link KPIs in real time and trigger make-before-break handover to keep every exchange inside the prescribed RCP limits. Moreover, HCATM fundamentally reshapes the economics and efficiency of air-ground communications by offloading the vast majority of non-time-critical traffic onto commercial broadband links. Whereas legacy VDL-M2 channels struggle under queuing delays and spectrum saturation at just 31.5 kbps, today's Non-Geostationary Orbit (NGSO) and GEO satellite networks, alongside 5G air-to-ground deployments, could deliver hundreds of megabits per second per aircraft. At the same time, this concept closes critical coverage gaps. Polar and remote routes, beyond VDL-M2's/LDACS' line-of-sight range, become reliably served by a constellation blend of LEO/MEO satellites. During climb and descent phases when satellite elevation angles dip, localized 4G/5G cells at major airports provide low-latency bursts that preserve service continuity. Perhaps most transformative is the dynamic latency optimization that HCATM would enable. GEO links alone impose roughly 600 ms round-trip delays [102], unsuitable for advanced interval management or remote-pilot assistance tools. By contrast, a LEO segment can reduce latency to below 70 ms [103], demonstrated ideal for mission critical data. A built-in performance monitor continually evaluates each path's delay, loss, and throughput in real time and switches high-priority traffic to the best available channel. Beyond raw capacity and coverage lies a compelling cost benefit. Airlines and ANSPs avoid procuring additional spectrum or installing new safety radios. Instead, modest software and firmware updates unlock the latent bandwidth of commercial networks already financed for passenger Wi-Fi and cabin services. This reuses existing Very Small Aperture Terminals (VSAT) and air-to-ground equipment investments, aiming to reduce the capital and operational expenditures for datalink providers. The resulting business case detailed [45] demonstrates clear returns within deployment windows.

3) SATELLITE-BASED VHF

Satellite-based VHF (SB-VHF) could expand today's 117.975–137 MHz direct controller-pilot communications (DCPC) and VDL Mode 2 datalink beyond the reach of

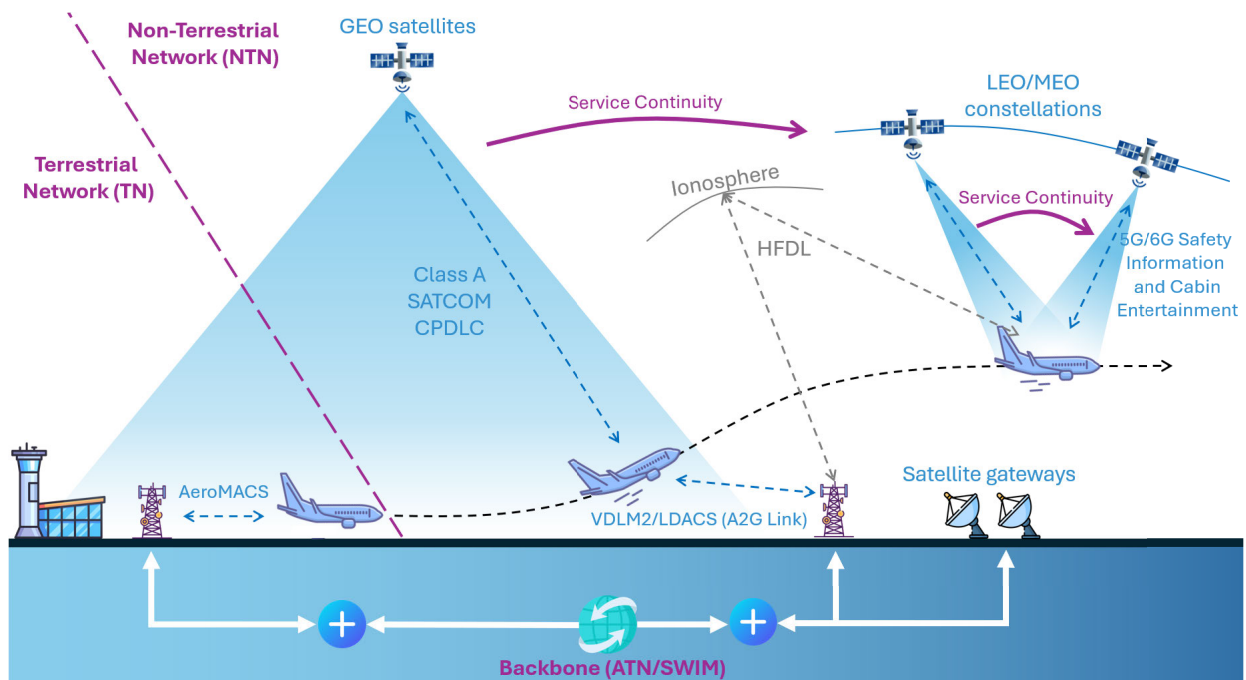


FIGURE 14. Gate-to-gate connectivity using hybrid TN/NTN.

terrestrial transmitters by relaying the same signals through LEO satellites. The concept is deliberately “avionics-transparent”: aircraft keep their standard VHF radios and antennas, while the space segment performs a bent-pipe relay that appears to crews and controllers as just another VHF ground station. With near-global footprints and low latency, SB-VHF is positioned to deliver continental-quality voice and data services in oceanic and remote airspace. The strategic aim of this concept is to access safety-critical voice and data communications over any airspace by integrating VHF DCPC and VDL Mode 2 services into a LEO satellite layer, without modifying aircraft radios. To achieve this, three main projects and their outcomes are listed below in Table 6. The phased deployment roadmap foresees completion of VOICE flight trials and Standards and Recommended Practices (SARPs) updates by 2026 [104], an initial 60-satellite operational constellation over the North Atlantic, North Pacific and polar corridors by 2028 [105], and global expansion with progressively reduced oceanic separations by 2030 [106], ultimately fusing terrestrial and space VHF layers into a harmonized communications fabric.

B. FROM OSI TO IPS: ARCHITECTURAL SHIFTS AND THEIR IMPLICATIONS FOR THE ON-BOARD ORCHESTRATOR

ATN/IPS [107] is ICAO's next-generation data-network architecture that will replace the legacy OSI ATN with a lean, IPv6-centric stack [108]. It adopts proven Internet technologies—IPv6, Mobile IP, Transmission Control Protocol (TCP)/User Datagram Protocol (UDP), TLS and Internet Protocol Security (IPsec) and welds them to aviation-specific

TABLE 6. SB-VHF projects.

Project	Scope & Milestones	Key Findings
VHF Over LEO Constellations for Europe (VOICE) (SESAR 3 JU VLD-02) [104]	2022–25 flight, laboratory and spectrum-compatibility tests over the Canarias and SAL FIRs; live traffic trials beyond 800 NM	LEO CubeSat relay sustained VHF voice and VDL Mode 2 links with legacy avionics; Doppler (± 3.2 kHz) and scintillation (< 5 dB) within tolerances; preliminary evidence supports halving oceanic longitudinal separation while cutting CO ₂ .
Space-Based VHF Asia-Pacific Region (APAC) Studies [105]	Link-budget, antenna-pattern and ionospheric analyses for a 1,000 km sat-to-aircraft range; contributions to International Telecommunication Union / Radiocommunication (ITU-R) Resolution 428	Feasibility confirmed with -93 dBm receiver sensitivity and 330 W satellite EIRP; recommended scintillation margins of 1 dB (mid-lat) and 5 dB (high-lat) plus ± 910 Hz Doppler pre-compensation for VDL Mode 2.
World Radiocommunication Conference (WRC) 2023 [106]	Global regulatory track to secure an AMS(R)S allocation across the full VHF band	December 2023 plenary concluded SB-VHF is technically and operationally compatible with existing AM(R)S/Aeronautical Radionavigation Service (ARNS) services, clearing the path for inclusion in the Radio Regulations.

requirements for safety, determinism and global mobility. In the ATN/IPS model every aircraft becomes an IP host that keeps a stable address while roaming across VDL Mode 2, LDACS, AeroMACS or satellite links; ground systems exchange routes with standard Border Gateway

TABLE 7. Technical contrasts between ATN/OSI and ATN/IPS.

Aspect	ATN/OSI (Doc 9705/9880)	ATN/IPS (Doc 9896)
Stack depth	7-layer OSI with X.25 SNDCEF, CLNP/IDRP, TP4, ULCS	4-layer IPv6 + TCP/UDP + IPS Dialogue Service
Routing & mobility	Path-vector IDRP advertises per-traffic-type routes; mobility = route updates	BGP-4+ on ground; Mobile IPv6 / Network Mobility Mobile IPv6 extension (NEMO) for aircraft
Transport behaviour	TP4 with per-segment ACK/NAK, long start-up	TCP (fast-start/CUBIC) or UDP + ROust Header Compression (ROHC) with Path-Maximum Transmission Unit (PMTU) discovery
Security hooks	ULCS byte-level handshake + ATN key agreement	IPsec/ Internet Key Exchange version 2 (IKEv2) at network layer, TLS at transport layer
Subnetwork integration	New datalink → bespoke SNDCEF/X.25 adaptation and security “colour” coding	IP-native links (LDACS, AeroMACS, SATCOM) appear as plain IPv6 hops

Protocol (BGP), while home agents and network-mobility extensions tunnel traffic seamlessly during hand-offs [109]. ATN/IPS has five main improvements over ATN/OSI which are listed in Table 7.

The practical impact of each change and how the orchestrator integration is influenced is listed below:

- Aspect 1, implies that ATN/IPS drops the OSI session/presentation layers as illustrated in Figure 15, and replaces the X.25 SNDCEF with straight IPv6 framing. Practically, every application PDU loses 40–60 bytes of header plus one or two round-trips of hand-shaking. For a VDL2 or LDACS bearer that translates into double-digit percentage savings in time-on-air and less Central Processing Unit (CPU) time in the avionics computer—important wins for latency-sensitive ATS traffic.
- Aspect 2 states that with ATN/OSI an aircraft change of ground station forces an IDRP path update that has to propagate across every inter-domain router before packets flow again. Mobile IPv6 short-cuts this: the aircraft updates its home-agent once, keeps the same care-of address, and the IP layer tunnels traffic while the routing plane stays quiet. For the orchestrator that means “make-before-break” handover can be driven by link metrics alone; it no longer has to wait for global route convergence.
- Aspect 3 relates to TP4’s strict per-PDU acknowledgements that were designed for noisy X.25 lines. Contemporary TCP variants (Bottleneck Bandwidth and Round-Trip Time (RTT) (BBR), CUBIC) ramp up faster and use selective acknowledgements, while UDP flows can be ROHC and protected by lightweight forward-error correction. The orchestrator can therefore rely on the transport stack itself to adapt to varying RF

conditions instead of second-guessing round-trip times and retransmission counts.

- Aspect 4 refers to security, specifically, ULCS security required custom key-agreement messages embedded in CM/CPDLC. Moving to IKEv2/IPsec (for network pipes) and TLS (for specific apps) puts key-exchange and cipher-suite negotiation into well-tested, off-the-shelf modules. Operationally, certificate management and crypto policy can be the same for avionics and ground routers.
- Aspect 5 impacts scalability of the network. Every time a new bearer (AeroMACS, future 5G NTN) is introduced, ATN/OSI needs a dedicated SNDCEF profile and route “colour” rules. In an IP world the link shows up as just another Layer-2 network advertising an IPv6 prefix. All QoS, filtering and fail-over is then handled by Differentiated Services Code Point (DSCP) markings and policy routing—tasks that fit naturally inside the ULCS/CM function where an on-board orchestrator can live.

Since ATN/IPS externalises mobility, security and congestion handling into well-defined Internet-grade mechanisms, the orchestrator can focus on its core job: measure live link KPIs and trigger predictive, make-before-break handover inside the mandated RCP/RSP windows. That tight scope makes implementation lighter, certification simpler and future expansions (additional radios, multi-SIM satcom, 5G) largely software-only. A complete orchestrator system must include the following four aspects:

1. Make-before-break handover: Mobile IPv6 protects session continuity, but it can’t tell when to switch links. The orchestrator, running as a CM/ULCS extension, can continuously score each active interface (Received Signal Strength Indicator (RSSI), Packet-Error Rate (PER), queue delay) and trigger the D-START/D-END pair on the new IPv6 path before RCPs are jeopardised.

2. Cross-layer KPI fusion: ULCS already terminates dialogue primitives; adding a light KPI broker here lets the aircraft correlate TCP retransmits, IPv6 neighbour-cache misses and real-time link metrics into a single “link health” vector.

3. Policy separation: ATN/IPS pushes QoS marking and security using Security Association Identifier (SA-ID) downwards. The orchestrator therefore only has to choose which interface and which DSCP per packet set; enforcement stays in the lower layers.

4. Minimal avionics footprint: Since the ULCS/CM process is already running in the cockpit network for CPDLC/CM, extending it with a deterministic state-machine adds no new Line-Replaceable Units (LRUs) and keeps certification changes local to the software part of the airborne router.

As ATN/IPS simplifies the plumbing—fewer headers, standard mobility, and built-in security, however, there should

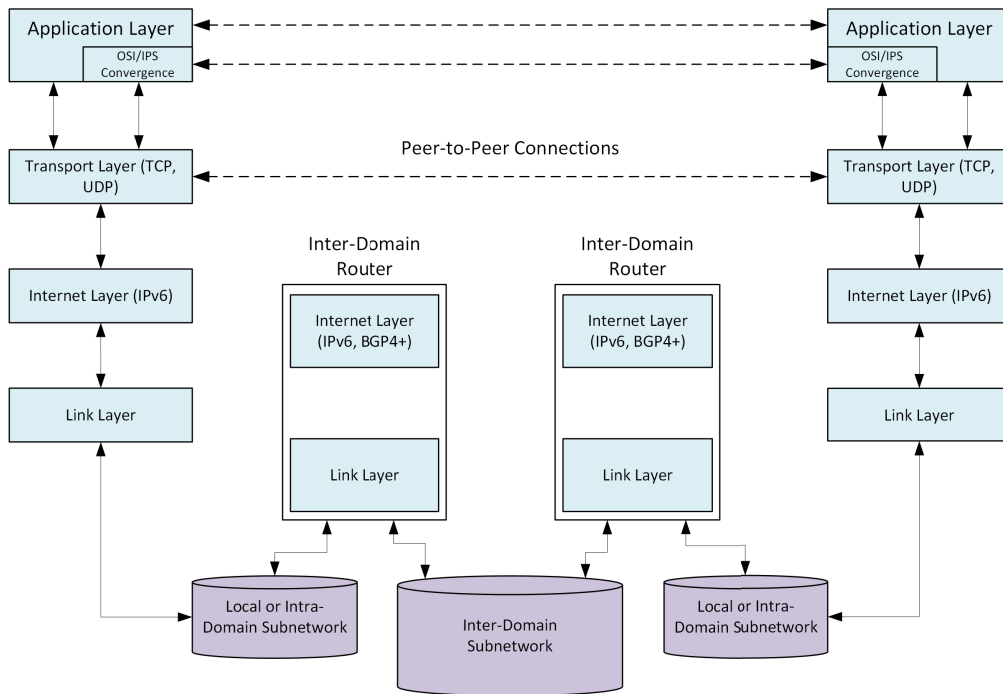


FIGURE 15. ATN/IPS protocol architecture.

still be considered an airborne decision-maker to keep safety-critical flows inside their RCP/RSP windows. Embedding that logic in the existing CM (ULCS) task gives us a certifiable, low-latency orchestrator without reinventing the protocol stack.

IV. EMPIRICAL FINDINGS AND COMPARATIVE ANALYSES

This section presents recent trends in research and proposes the orchestrator's usage and applicability in high-end scenarios, concluding with a comparative analysis between dynamic adaptable algorithms for each scenario.

There are numerous studies about future aircraft communications converging to a single conclusion that there is a need for heterogeneous, policy-driven communications fabric rather than a dominant "silver-bullet" link in the near future. Study [110] surveys Future Aerial-COMmunications (FACOM) research, detailing the connectivity demands of airplanes, electrical Vertical Take Off and Landing (eVTOL), and drones and matching them to cellular, satellite, HAP, and A2A technologies. It clearly shows that no single link can satisfy all safety-critical and high-throughput needs, underscoring the value of heterogeneous, multi-technology networks. Extending that insight, [111] shows Aeronautical Ad-hoc Networks (AANETs) as the linchpin for future in-flight connectivity, after first benchmarking today's satellite and 4G/5G air-to-ground options. Complementary surveys dig deeper into individual bearer families. Study [112] compare AeroMACS, LDACS and Airborne New Advanced

Satellite Techniques & Technologies in a System Integrated Approach (ANASTASIA) against mobility, security and handover latency constraints in the ATN/IPS roadmap and [113] audit multidisciplinary aircraft-design tool-chains, revealing that on-board data-link sizing is still disconnected from early-stage vehicle optimisation. Reference [114] prototype a Quick UDP Internet Connections (QUIC) inspired transport layer that sustains 99.99% delivery probability across intermittent A2G paths. Reference [115] catalogs machine-learning and deep-learning techniques—ranging from Convolutional Neural Network (CNN) spectrum sensing to multi-agent reinforcement learning for beam hopping—that can turn this patchwork of bearers into a cohesive, self-optimising network. Moreover, [116], [117], [118] explore the utilization of DL/RL for decision making in fine-tune UAV-RIS trajectories and phase shifts, coordinate multi-agent routing, and adapt satellite beam-hopping. From a link-reliability viewpoint, Tariq et al. show that adding GNSS-synchronised Time-Triggered Ethernet keeps UAV-to-ground jitter below $60 \mu s$ but can lift worst-case latency to ~ 3 ms when a wireless hop is present [119]; Top-Flight Satcom rack trials record ~ 250 ms round-trip voice/data delay with Mean Opinion Score (MOS) > 4 [120], Iridium-NTN emulation maps 10° – 90° elevation to 2–18 kbs $^{-1}$ throughput and 40–420 ms one-way delay [103], and a companion A2G link-budget shows the path stays closed above 5 GHz only with ≥ 14 dBi onboard gain and adaptive coding [121]. Together, these studies converge on the urgent need for an intelligent onboard system to manage dynamic links.

TABLE 8. AI-driven orchestrator for next-gen airborne link management.

Driver	Legacy Limitation	AI-Enabled Advantage
Dense multi-link stack (ground and space)	Rule set grows $O(N)$; heuristic handover tables become unmanageable	RL/DL policies abstract the state; scalability governed by model size, not hard-coded rules
Trajectory-dependent coverage	Pre-computed tables invalid after reroutes or re-clearances	Sequence models forecast link KPIs along 4-D flight path
High-dynamics + airframe shadowing	RSSI thresholds trigger too late; frequent blackouts during steep maneuvers	Contextual bandits / actor-critic RL fuse 6-DOF data with KPIs to pre-empt signal loss and switch links earlier
Congestion & tariff variation	No mechanism to balance load or minimise data-link charges	Multi-attribute decision + Deep Reinforcement Learning (DRL) trade QoS, cost and RCP compliance in real time

pt

Jumping back to the orchestrator hypothesis onboard the aircraft, this system is conceived as a real-time decision engine that supervises all radios capable of safety-critical and non-safety traffic. The considered links are still to be determined but a complete list would include VDL-M2, SB-VHF, GEO/LEO Satcom, LDACS, AeroMACS, HFDL, and future 5G/6G A2G cells. This orchestrator would have three main requirements:

- Maintain continuous compliance with ICAO RCP/RSP targets under all flight regimes.
- Optimise end-to-end QoS by keeping track of link parameters.
- Provide a single interface to CM in ATN/IPS, by selecting “best-link” as an abstract bearer to higher applications (CPDLC, ADS-C, A-ID, IFEC back-haul).

This orchestrator could be installed in Aircraft Control Domain (ACD), co-located with the secure airborne router or communications management unit (CMU). It could run on the same DAL-B/C processing module that currently hosts ULCS/CM. No additional LRUs are introduced; only a partitioned software load is required. The input/output (I/O) interfaces are ATN/IPS dialogue service and health-monitoring bus (north-bound) and radio managers for each sub-network along with attitude/flight-data from the Avionics Full-Duplex switched ethernet (AFDX) backbone, and optional network-load feeds from CSPs (south-bound). Since the orchestrator never injects raw flight controls, compliance falls under DO-178C Design Assurance Level C (DAL-C) [122] with independence for safety monitors; deterministic fall-back rules guarantee link selection if the AI component is unavailable. Legacy link-management logic cannot cope with tomorrow’s operational envelope as listed in Table 8:

A. SCENARIO EVALUATION

To benchmark decision-making algorithms in a manner that reflects real-world airline operations, two complementary

evaluation scenarios are defined. Since the search space created by multi-constellation SATCOM, 5G/6G A2G cells, and legacy VHF/HF links is far too large for static tables, the orchestrator’s software layer must embed machine-learning components that can learn, adapt, and still remain verifiable under DAL-C constraints. Accordingly, the study below compares several candidate decision engines (rule sets, deterministic optimization, reinforcement learning, and hybrid models) across the two scenarios, so that the orchestrator could incorporate an algorithm/combination of algorithms that yields the best blend of RCP/RSP compliance, QoS, and operating cost.

- 1) Scenario I: Nominal Flight-Plan Execution. The aircraft proceeds gate-to-gate along its cleared Instrument Flight Rules (IFR) route with only routine altitude and speed adjustments. Since the trajectory is known in advance, the orchestrator can exploit deterministic context using waypoint sequence, scheduled sector entry times, and published radio-coverage footprints for preemptive handover. The emphasis here is on predictive or planning-oriented intelligence that minimizes interruptions and triggers make-before-break network switches under normal operating conditions. The input data for this scenario are the flight plan and 4D trajectory (waypoints, altitudes, estimated sector times), radio network topology (coverage maps, cell transition), and link live KPIs (QoS/LBA parameters)
- 2) Scenario II: Dynamic Deviation and Maneuvers. In this scenario, unforeseen events such as ATC reroutes, convective weather avoidance, or TCAS resolution advisories force the aircraft to deviate from its filed path and adopt aggressive bank or pitch angles that may temporarily shadow antennas. Trajectory forecasts lose operational relevance, and link quality may degrade severely or collapse altogether, with outages exceeding 30 seconds as reported in [13]. In this setting, the orchestrator must transition from prediction to adaptation, relying on real-time link quality indicators, antenna visibility, and instantaneous aircraft dynamics to perform rapid, reactive link switching and reallocation. The input data here are real-time flight dynamics (bank angle, pitch, roll rate, acceleration), Link live KPIs (QoS/LBA), antenna geometry and blind-spot modeling in relation to airframe pose, interference factors (weather, link congestion).

For each of the operational scenarios described above, Table 9 outlines a curated shortlist of algorithmic approaches that could be employed by the onboard orchestrator to support real-time or predictive link management. Here, the algorithms are categorized based on their possible applicability to scenarios. Each entry includes the algorithm type, a classification of its operational characteristics.

This analysis’ scope is to assess possible algorithms for decision making. In the referenced studies, certain

TABLE 9. Comparative analysis of AI algorithms for decision-making with applicability in link selection.

No.	Algorithm	Type	Scenario		Algorithm Strengths	Ref.
			I	II		
1	Proximal Policy Optimisation (PPO)	RL (Deep)	✓	✓	<ul style="list-style-type: none"> Clipped-surrogate updates prevent large policy jumps Works with discrete and continuous link choices without heavy retuning Sample training for fast adaptation to trajectory or channel degradation 	[123]–[126]
2	Dueling/ Double Deep Q-Network (DQN)	RL (Deep)		✓	<ul style="list-style-type: none"> Dueling+Double heads give low-bias, fast-converging Q-values for volatile wireless links Scales to large discrete choices with lightweight, fully decentralised training Proven to cut delay/energy and hit strict QoS targets vs. heuristic and single-agent baselines 	[127], [128]
3	Contextual Multi-Armed Bandit (UCB / Thompson)	RL (light)		✓	<ul style="list-style-type: none"> Stateless Upper Confidence Bound (UCB) learns “best relay” on-the-fly—logarithmic regret, no channel model or training data needed Directly minimises composite Age of Information (AoI) (mean + violation) - sharper freshness under volatile 5G links Ultra-lightweight: per-source computation $\mathcal{O}(K)$, one-hop feedback only—fits battery PMUs or dense grids 	[129], [130]
4	Hierarchical Reinforcement Learning (HRL)	RL	✓	✓	<ul style="list-style-type: none"> State–Action–Reward–State–Action (SARSA) triggers handover, neuro-fuzzy Graph Neural Network (GNN) picks the RAT (mmWave/Long-Term Evolution mobile (LTE)/Dedicated Short-Range Communications (DSRC)), and fuzzy cluster routing chooses the path. SARSA keeps Vhandover failures below 2% at 100 km h⁻¹; the GNN condenses six fuzzy QoS rules for fast RAT ranking. QoS gains over Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Access Network Discovery and Selection Function – Handover (ANDSF-HO), V2I-MoLoHA: PDR +65 %, delay -50 %, throughput +50 %. 	[131]
5	Long Short-Term Memory (LSTM)	DL	✓		<ul style="list-style-type: none"> Bayesian-optimised LSTM forecasts User Equipment (UE) trajectory /RSS to trigger handover early, then a speed/-bandwidth screen prunes the RAT list before ranking. Fuzzy-AHP gives subjective weights, entropy gives objective weights, combined to score bandwidth, delay, jitter, loss and cost and lock the target cell only if its utility beats the current one by a δ margin. Failure probability ↓42.1 %, mean delay ↓68 %, while keeping load balanced across Wireless Local-Area Network (WLAN), LTE and 5G access. 	[132], [133]
6	Temporal Convolutional Network (TCN)	DL	✓		<ul style="list-style-type: none"> Att-Sequence Generative Adversarial Network (SeqGAN)-TCN couples dilated temporal convolutions with multi-head self-attention and SeqGAN augmentation to forecast link traffic; RMSE/Mean Absolute Error (MAE)/ Mean Absolute Percentage Error (MAPE) drop markedly, yielding an average 67.04% accuracy boost over single-model baselines. These forecasts feed an Improved Adaptive Ant Colony (IAAC) scheduler that ranks routes by pheromone, hop distance, composite cost (delay+loss) and predicted utilisation, then applies a dynamic bandwidth threshold to pick the least-congested provincial–national DC path. Tested on State Grid traces under Mininet, IAAC pushes mean link utilisation to about 85% (Equal-Cost Multi-Path 40 %) and lowers delay, giving a 27.6% gain in end-to-end transfer timeliness for two-level data-centre traffic. 	[134]
7	GNN on coverage / trajectory graph	DL	✓		<ul style="list-style-type: none"> Each UE exchanges only two rounds of $P_{R,ij}$ messages for local decisions without constellation-wide state. Penalty term $\text{ReLU}(\sum_j p_{i,j} - P)$ keeps per-satellite quota violations to just 0.38 %, virtually eliminating handover failures when combined with a 3-case ACK rule. One model generalises across UE densities and, in a 1 584-satellite / 22-orbit Systems Tool Kit (STK) run, boosts average UE rate by ≈ 35 % over the best greedy baseline. 	[131], [135]
8	Random Forest	Other (ML)		✓	<ul style="list-style-type: none"> Built-in feature ranking is resilient to missing values and prunes redundant attributes for less input set while conserving accuracy. The forest reaches > 99% accuracy/MCC and consistently beats SVM, Hoeffding Tree / Hoeffding Adaptive Tree (HT/HAT) and other baselines on both AS-link discovery and Wi-Fi handover tasks. Sub-sampling and tree-level parallelism keep classification latencies in the few-ms range. 	[136], [137]

assumptions and input parameters were utilized, therefore, adoption of such methods for Scenario I & II must include modifications to system design and optimization.

PPO core can satisfy both of our evaluation scenarios. Researchers in [124] show PPO increased total completed bits by 25–60% over Advantage Actor-Critic (A2C) and

TABLE 9. (Continued.) Comparative analysis of AI algorithms for decision-making with applicability in link selection.

9	Extreme Gradient Boosting (XGBoost)	Other (ML)	✓		<ul style="list-style-type: none"> This tree captures complex non-linear interactions, lifting AUC by 3.9–5.3% and uncovering up to 24% more hidden AS links than prior baselines once trained on only the 35 most informative features. XGBoost's built-in regularisation, missing-value routing and shrinkage prevent overfitting. Histogram splitting, parallel tree construction and lightweight Grey Wolf-guided hyper-parameter search deliver strong models with low time-to-train and modest compute, scaling smoothly to 4×10^5 links and 8×10^4 nodes. 	[136]
10	Fuzzy-Logic Controller (FLC)	Other (rule)	✓	✓	<ul style="list-style-type: none"> FLC fuses five heterogeneous inputs (Reference-Signal Received Quality (RSRQ), UE mobility, (H)evolved Node B (eNB) / Wi-Fi load, back-haul load and service latency-sensitivity) to yield a single "RAT-suitability" score. Hot-spot 2.0 beacons and a lightweight local-ANDSF cache expose coarse load states for Wi-Fi APs and LTE (H)eNBs. Updates are pushed only on threshold crossings—no per-UE polling—so overhead is negligible. In Network Simulator 3 (ns-3) simulations of an indoor-mall scenario (2 macros, 5 femtos, pedestrian UEs) the FLC cuts total handover by up to 85% versus legacy LTE A2/A4-RSRQ triggering. By steering low-speed users toward lightly-loaded small cells and keeping high-speed users on macros, downlink and uplink throughput rise ≈ 300 kbit/s per UE at high femto load, and average packet delay is consistently lower than the baseline across all load points. The second study shows that feeding observed average handover (HO_{avg}) and system throughput into a Mamdani FIS can output near-optimal Handover Margin (HOM), Time-to-Trigger (TTT), α and β parameters for four standard LTE handover algorithms. With only nine simple rules the fuzzy optimiser boosts throughput by up to 5.6% and slashes handover by 59–83%. Since the controller reasons over abstract linguistic states rather than raw metrics, adding new RATs (5G/6G, NTN, NR-FR2, Wi-Fi 7) or extra inputs (energy, SLA cost, slice priority) is straightforward—just extend the rule base. 	[138], [139]
11	Adaptive Neuro-Fuzzy System (ANFIS)	Hybrid	✓	✓	<ul style="list-style-type: none"> A Multilayer Perceptron (MLP) learns each Primary User (PU)'s ON/OFF pattern ($\approx 95\%$ accuracy). If the predicted busy span on the current channel exceeds a computed handover cost (switch delay + re-config + contention factor), the SU launches a proactive spectrum handover; otherwise it waits, avoiding needless moves. ANFIS fuses fuzzy rules and neural learning to score every idle channel with a channel-advantage function that blends predicted idle time, Signal-to-Interference-plus-Noise Ratio (SINR) and raw data rate; only channels with a score > 1 are considered and the top scores are assigned first to waiting SUs. NS-2/CRAHN tests (10 PU channels, 1 SU) show an almost flat handover count as PU load rises and a $\sim 10\%$ throughput gain over reactive schemes, thanks to cost-aware initiation and learned channel ranking. 	[140], [141]
12	Hybrid TOPSIS + Q-Learning	Hybrid		✓	<ul style="list-style-type: none"> A multi-criteria AHP-TOPSIS filter weighs downlink Reference-Signal Received Power (RSRP)/RSRQ, uplink SINR, current load, and UE direction/location to rank neighbouring cells; top-ranked eNBs are matched to UEs according to the UEs' own AHP-TOPSIS priority, but this could be adapted to above described scenarios The Q-learning agent observes each UE's average speed state and updates a Q-table to choose the (Hysteresis, TTT) pair that minimises too-early/too-late failures and ping-pong. In a 19-cell LTE-A layout (40 UEs, 3–120 km/h) the hybrid scheme cuts the handover failure rate by $\approx 28\%$ and the ping-pong rate by $\approx 35\%$ versus the RSRP-only baseline, and by $\approx 25\%$ / $\approx 33\%$ compared with the Fuzzy-TOPSIS (FMCCS) method. 	[142]

Deep Deterministic Policy Gradient (DDPG) (approximately 16 Mb versus 10 Mb at $K = 24$), and reached its reward plateau in fewer than 0.6 million steps. When link quality fluctuates abruptly, a PPO mm-wave scheduler reduced the mean per-packet delay to 25.6 ms (compared to 44 ms under a bandit baseline). This has been achieved

while maintaining main-link outages below 5 %. In [126] Independent PPO (IPPO), reduced redundant base-station handover by 82% and sustained RSRP above -80 dBm on complex 3-D UAV routes. These results demonstrate that PPO is capable of learning reliable, trajectory-aware communication plans for Scenario I, while also reacting

TABLE 10. Comparison of algorithmic properties for multi-link orchestration under different scenarios.

Scenario I – Nominal Flight-Plan Execution					
No.	Algorithm	Training Data Req.	Sample Efficiency / Convergence	Robustness to Non-Stationarity	Computational Footprint
1	PPO	–	Learns reasonably fast with a high-fidelity simulator	Moderate – clipped updates resist drift	High
2	HRL	–	Slow: sub-policy and planner need many episodes	Moderate - abstraction shields variations	Very High
3	LSTM	✓	Supervised fit; fast inference post-training	Low - needs retraining for new trajectories	High
4	TCN	✓	Faster than LSTM; handles long sequences	Low–Moderate	Medium–High
5	GNN	✓	Needs large labeled trajectory dataset	Moderate - retrain tolerates topology change	High
6	XGBoost	✓	Quick fit on KPI/waypoint features	Low - poor under distribution shift	Low–Medium
7	Fuzzy Logic	–	Instant — rule base from expert knowledge	High - tolerates input noise well	Low
8	ANFIS/DHNN	✓	Hybrid training	Moderate - slow drift ok, fast shocks less so	Medium
Scenario II – Dynamic Deviations and Maneuvers					
9	PPO	–	Moderate - updates every 10^2 – 10^3 steps	Medium - clipped updates resist some drift	High
10	Dueling DQN	–	Poor–Moderate - needs replay memory	Low–Medium - degrades under reward shift	High
11	Contextual Bandit (UCB)	–	High - adapts with few samples	High - tracks link fade/antenna shadow fast	Low
12	HRL	✓	Slow - two-layer structure needs training	Medium - top-layer remains static	Very High
13	Random Forest	✓	Fast offline training and immediate use	Low - retrain needed for new flight paths	Low–Medium
14	Fuzzy Logic	–	Instant — rule base by hand/tuning	High - handles KPI drift well	Low
15	ANFIS/DHNN	✓	Moderate - minutes on 10^4 samples	Medium - adaptive layer helps with drift	Medium
16	Hybrid TOPSIS + Q-Learning	✓	Moderate - offline TOPSIS, online Q-update	Medium–High - handles KPI drift well	Medium

quickly enough to handle shadowing, congestion, and dynamic reroutes under Scenario II. Reference [127] have shown that in an interference-limited Vehicle-to-Vehicle (V2V) setting similar to Scenario II, a federated DQN maintained over 90% of V2V packets within the 100 ms delay budget, even with 30 simultaneous transmitter-receiver pairs. In [130], researchers have shown UCB bandit can re-rank candidate links instantly using only the current feature vector, the LinUCB-VA implementation in a post-disaster SAGIN testbed. The total data delivery resulted to approximately 9.2 Gbps with 20 visible LEO satellites. This makes it a lightweight, quick-to-adapt choice for Scenario II. However, [131] demonstrates that by combining a SARSA trigger with a neuro-fuzzy GNN selector they reduced vertical handover failures to below 2% at 100 km h^{-1} , while increasing packet delivery ratios by approximately 65 %. Meaning this approach could offer the agility required for predictive link scheduling in Scenario I and the robustness needed for fast

switching in Scenario II. As shown in [133], Bayesian-optimised LSTM can exploit the known 4-D flight plan to forecast location and link quality with approximately 99% accuracy which is optimal for Scenario I. Similarly, [134] have shown to raise link-load prediction accuracy by 67% and cut end-to-end transfer timeliness by 27.6% in a two-tier backbone. Another DL approach which is strong for Scenario I is implemented in [135] and results that GNN handover strategy for LEO constellations keeps satellite-to-UE load-balancing violations below 0.4 %. Alternatively, for Scenario II, random forest models implementation in [137] have shown they can react at “dynamic-deviation speed” with 99.7% accuracy. Outside RL/DL approach, XGBoost is ideal for Scenario I because its tree ensemble can pre-learn the non-linear interactions between waypoint-indexed coverage windows as shown in [136]. Best for both scenarios, fuzzy logic controller [138] approach sets “RAT-suitability” score and supports throughput over LTE baselines in both stable and

volatile channel conditions. However, their rule base grows quickly with each extra KPI, so adding new radios demands costly re-tuning and validation. Despite the above studies, a hybrid approach is very attractive for both scenarios. ANFIS is one of the hybrid algorithm approach. It merges learned PU-activity forecasts with fuzzy channel scoring, and has been shown to hold handover numbers almost constant while boosting SU throughput by 10% in cognitive-radio trials in [140], and by using an ANFIS variant could lower switch delay to 1.1 s and packet loss to 5% in heterogeneous networks demonstrated in [141]. From this perspective, a hybrid approach is a scenario-focused option for the orchestrator. Another hybrid approach is outlined in [142] where AHP-TOPSIS pre-filters candidate links while a lightweight Q-learning agent continually tunes (Hysteresis, TTT) pairs. This results in handover failure and ping-pong rates lower by 28% and 35% respectively compared with fuzzy-only baselines making this approach more attractive for the fast-reactive maneuvers (Scenario II).

To evaluate the candidate algorithms for deployment on an airborne module, three implementation criteria become essential. First, sample efficiency and convergence determine how quickly an agent can be trained to a usable level. In Scenario I, the full trajectory is known in advance, so methods that require extensive offline training such as supervised LSTMs fitted to historical waypoint/KPI logs are acceptable as long as they quickly reach their performance plateau. By contrast, Scenario II demands rapid online adaptation: an algorithm must learn to recognize and recover from unexpected reroutes or antenna shadowing within only a few episodes or flight minutes. Contextual bandits or lightweight policy-gradient methods that converge in tens to hundreds of steps can thus be rolled out almost immediately, whereas any hierarchical or replay-buffer-based approach that takes thousands of simulated steps risks being obsolete before it finishes training. Another perspective is robustness to non-stationarity which measures how a policy degrades when real-world conditions drift, whether link budgets change as satellites become congested, tariffs fluctuate, or the airframe unexpectedly blocks an antenna during a steep maneuver. In Scenario I, flight plans and coverage footprints are largely deterministic, so occasional clipping or fixed-rule updates suffice to handle minor load shifts; periodic retraining once per release cycle may be acceptable. In Scenario II, however, performance must remain acceptable even as the statistical distribution of link KPIs shifts on the order of seconds: model-free RL with clipped or double estimators, or simple fuzzy-logic fallbacks, are better able to tolerate abrupt fades and topology changes than mostly offline supervised regressors that require retraining for every new path or link failure pattern. The computational footprint assesses if inference meets a 100 ms deadline on an ARINC-653 partition without GPU support. Scenario I permits heavier models if they stay within timing limits, while Scenario II demands lightweight methods to ensure sub-100 ms handover. Even policy-gradient agents such as PPO

may require distillation or quantization to meet this deadline under rapid maneuvers and intermittent data. By organizing every algorithm along these three axes for each scenario, Table 10 exposes the hidden trade-offs.

This perspective promotes PPO and HRL for Scenario I because they can learn trajectory-aware routing without labelled data, but demand heavy CPU. Supervised predictors (LSTM, TCN, GNN, XGBoost) train quickly on KPI/waypoint logs and run fast on-board, yet must be retrained when coverage maps drift. Fuzzy-logic and ANFIS/DHNN controllers execute almost instantly and handle moderate KPI shifts, but cannot model complex trajectory effects. Scenario II places tighter 100 ms decision and robustness limits. Contextual bandits excel: they need no offline data, adapt in a few samples, and run in micro-seconds—ideal for sudden shadowing. Fuzzy rules again provide a low-overhead safety net. Deep RL (PPO, Dueling DQN) converges more slowly and incurs higher inference cost, while HRL or hybrid TOPSIS + Q-learning exceed CPU budgets during fast link outages. Hence no single algorithm dominates both scenarios. Predictive supervised or deep-RL schedulers suit Scenario I when periodic retraining is possible; bandits and fuzzy controllers are the only methods that consistently meet sub-100 ms deadlines in Scenario II. A hybrid stack supervised/RL planners for planned handover, with bandit or rule fall-backs for rapid reactive switching, offers the most practical solution.

B. PROOF-OF-CONCEPT FOR LSTM-PPO PERFORMANCE IN SCENARIO I

This section presents an initial proof-of-concept evaluation of a RL link-selection agent that couples PPO with a gated LSTM backbone. The preliminary results that follow demonstrate that this approach can rapidly learn to anticipate fast channel changes and outperform the best heuristic in both selection accuracy and mean reward. Performance is expressed in terms of link-selection accuracy and mean per-step reward, providing quantitative evidence that a sequence-aware RL controller can exploit deterministic trajectory context to reduce make-before-break interruptions under Scenario I conditions. The dataset used for the agent training is a combination of LTE down-link traces gathered during drive tests on urban buses, regional trains, and highway cars [143]. To emulate the triple-link setting of Scenario I, three independent channel sequences are drawn from the archive and aligned in time, producing a nine-element observation vector:

$$\begin{aligned} [RSRP_1, RSRQ_1, SNR_1, \\ RSRP_2, RSRQ_2, SNR_2, \\ RSRP_3, RSRQ_3, SNR_3] \end{aligned} \quad (1)$$

Here, RSRP is reference-signal received power, RSRQ is reference-signal received quality, and SNR is the down-link signal-to-noise ratio for each synthetic link. The raw logs totaling ≈ 10 h of mobility over ≈ 600 km are concatenated,

resampled to 2 Hz, cleansed of outliers, and z-normalised; fewer than 0.3% missing samples are mean-imputed. The resulting multi-link sequence supplies realistic yet deterministic channel dynamics that match the predictive handover problem posed in Scenario I. While dedicated aeronautical KPI traces would be the ideal benchmark, collecting them entails instrumented flight trials or high-fidelity environment generation, which is outside the scope of this proof-of-concept; the terrestrial LTE corpus therefore serves as a pragmatic proxy that is sufficient to demonstrate the learning potential of the PPO–LSTM approach.

As a general overview of RL, it formalizes sequential decision-making as an interaction between an agent and an environment modeled by a Markov decision process. At every timestep the agent observes a state vector, selects an action, and receives a scalar reward that quantifies the utility of that action with respect to a long-term objective [144]. Policy-gradient methods adjust the agent's action probabilities so as to maximize the expected discounted return, allowing the policy to improve directly from sampled experience rather than from supervised labels. In the present study the state is the nine-element KPI vector shown above, the action is the index of the chosen radio link, and the reward is a weighted combination of throughput and make-before-break continuity. Formulating link selection as an RL problem permits the agent to discover hand-over policies that exploit both instantaneous signal quality and longer temporal patterns in Scenario I. Also, PPO is added, which is a first-order policy-gradient algorithm that constrains the per-update change in the policy by clipping the likelihood ratio between new and old policies [145]. The surrogate objective strikes a balance between sample efficiency and numerical stability, eliminating the need for delicate trust-region computation while still preventing destructive policy oscillations. PPO therefore scales well to problems with high-dimensional, continuous observations such as the KPI sequence considered here. In this work a single-headed PPO actor–critic network maps the current LSTM hidden state to (i) a categorical distribution over the three candidate links and (ii) a state-value baseline; clipped updates with ϵ and entropy annealing encourage steady improvement without premature convergence to sub-optimal deterministic choices. For storage dependencies, LSTM is used which extends recurrent neural networks with input, forget and output gates that mitigate vanishing-gradient effects [146]. Here, a single LSTM layer with 128 hidden units ingests the resampled KPI stream and outputs a compact embedding that captures both the current link quality and its recent evolution. By integrating this temporal representation into the PPO, the agent is equipped to anticipate upcoming degradations of the link. The algorithm's logic can be seen in Figure 16 where it initiates with start-up and configuration. Then the link selection environment is built from the KPI trace and instantiates the agent's components which are the LSTM backbone, PPO actor-critic heads and rollout buffer. Control then enters a

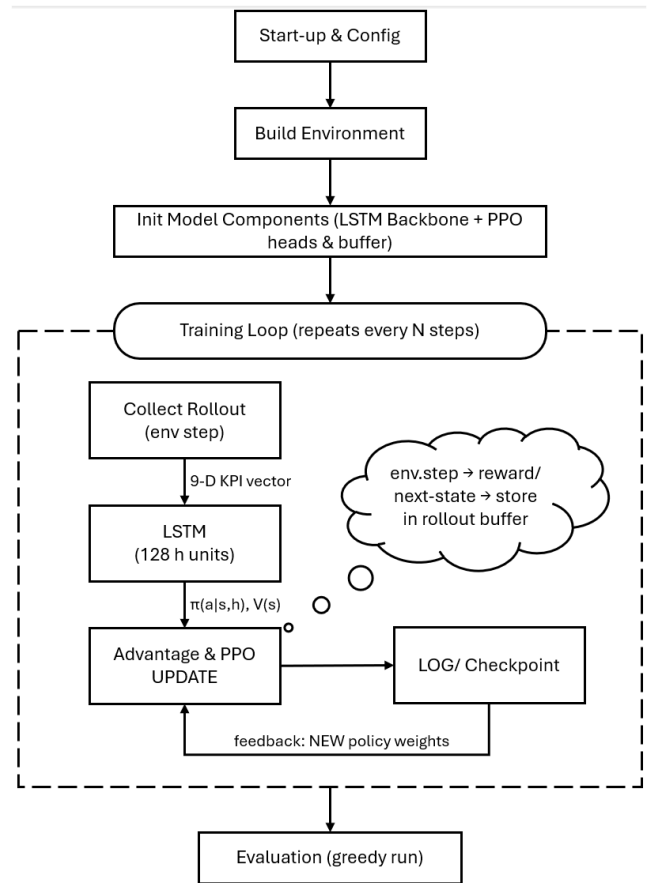


FIGURE 16. Logic overview of PPO–LSTM agent.

recurrent training loop: at each step the environment supplies a nine-dimensional KPI state, which the LSTM compresses into a hidden representation that feeds the policy and value estimators. The selected action is applied to the environment, the resulting reward and next state are stored in the buffer, and advantage estimates drive a clipped PPO update that refreshes all network parameters. Two feedback paths close the loop: the updated policy is used immediately to collect the next batch of experience, and periodic checkpoints preserve weights and metrics for later inspection. When the prescribed number of updates is complete, the best checkpoint is run in a greedy (exploration-free) mode to quantify link-selection accuracy and average reward, producing the preliminary results reported below. The reward assigned to each timestep is a simple “hit/miss” signal that compares the agent's choice with the link that has the highest composite signal score:

$$Score_j(t) = \sum_{i=1}^3 w_i m_{i,j}(t), \quad j \in \{1, 2, 3\} \quad (2)$$

The best-performing link at each t is selected as the one yielding the highest aggregated signal score:

$$j^*(t) = \arg \max_j Score_j(t) \quad (3)$$

TABLE 11. Key hyper-parameters for PPO-LSTM training.

Category	Parameter	Value
Optimisation	Initial learning rate lr_0	1.2×10^{-3}
	PPO clip range ϵ	0.15
	Discount factor γ	0.99
	GAE parameter λ	0.95
	Entropy coefficient β	$0.008 \rightarrow 0.001$
	Critic loss coefficient c_v	0.25
Batching	Rollout size N_{traj}	64 episodes
	PPO epochs K	4 per update
	Mini-batches	8 per epoch
Network	LSTM hidden units	128
	Embedding dimension	64
	Sequence length	64 steps
	Maximum episode length	2048 steps

Therefore, the reward is defined by the following:

$$r_t = \begin{cases} +R, & \text{if } a_t = j^*(t), \\ -R, & \text{otherwise,} \end{cases} \quad (4)$$

where

- $m_{i,j}(t)$ is the i^{th} metric (RSRP, RSRQ, SNR) of link j at time t ;
- $\mathbf{w} = [w_1, w_2, w_3]^T$ is a metric-weight vector (default $w_i = 1$);
- a_t is the action output by the policy (index of the chosen link);
- $R = 10$ is the positive reward scale.

With the default weights, the composite score simplifies to:

$$\text{Score}_j(t) = \text{RSRP}_j + \text{RSRQ}_j + \text{SNR}_j \quad (5)$$

Thus the agent receives +10 whenever it picks the link whose summed KPI is largest, and −10 otherwise, directly encouraging accurate selection of the best-quality link.

The end-to-end training flow is governed by a set of fixed hyper-parameters listed in Table 11.

The learning curves in Figure 17 quantify how quickly the PPO-LSTM controller discovers an optimal policy. Subfigure 17a panel shows a smooth, monotonic rise in per-step return from near zero at initialization to +9.7 by update 385, at which point the curve clearly saturates. Since the reward function assigns +10 for a correct link choice and −10 for a miss, this trajectory implies that the agent moves from random-chance performance (approximately 50% hits, average reward ≈ 0) to making the correct decision more than 98% of the time. Similarly, Subfigure 17b charts selection accuracy over training showing that thanks to the supervised warm-start, the run begins above the random 0.33 line at ≈ 60 ; accuracy then climbs steadily, breaking 0.70 by step 100, crossing the 0.90 and 0.95 thresholds at steps 254 and 303, and finally plateauing near 0.97. For assessing the loss, Subfigure 17c tracks the PPO actor loss which is the clipped surrogate objective. Early in training, the curve shows large positive and negative excursions (up to ± 0.03) because advantages are still high and the likelihood-ratio r_t often exceeds the clipping bound $\epsilon = 0.15$. After roughly 150 optimization steps, the variance collapses and the

smoothed trace hovers symmetrically around zero, meaning that most updates fall inside the trust region and deliver almost no incremental gradient. The absence of any upward drift or widening spread indicates that the policy is not oscillating or diverging. Also, in Subfigure 17d evolution of policy entropy (Shannon entropy $H[\pi_t]$) of the soft-max logits is produced by the actor head. The trace begins low ($\approx \ln 3$), which is the entropy of a uniform distribution over the three links, and then decays smoothly by update 400. This behavior tells that the coefficient β_t multiplies the $-\beta H$ term and is linearly reduced from 0.008 to 0.001, encouraging broad exploration early on and progressively tighter, near-deterministic policies once sufficient experience has been gathered. Although Subfigure 17e looks as if the loss is increasing, this is not true; it is a consequence of the formula:

$$L_{\text{tot}} = L_{\pi} + c_v L_V - \beta H[\pi], \quad (6)$$

where L_{π} is the clipped PPO surrogate, $L_V = \|V_{\theta}(s_t) - \hat{R}_t\|_2^2$ is the mean-squared value error, $c_v = 0.25$, and β is a small entropy weight. As the agent's accuracy approaches 1.0, the undiscounted returns $\hat{R}_t$ that feed the critic grow toward $10 \times 2048 \approx 2 \times 10^4$; squaring those targets drives the error term L_V into the 10^5 – 10^6 range, minimizing the actor and entropy contributions and producing the increase seen here. Because the actor loss has already collapsed (Fig. 17c) and the KL constraint keeps policy updates small, this growth in L_V (and in the total loss) shows that the critic is tracking larger positive returns, not that training is diverging. In short, the upward slope is expected and compatible with the high reward and accuracy achieved by the agent. Finally, Subfigure 17f plots the per-update Kullback–Leibler (KL) divergence as per the following formula:

$$D_{\text{KL}}(\pi_{\text{old}} \parallel \pi_{\text{new}}) = \mathbb{E}_{a \sim \pi_{\text{old}}} \left[\log \frac{\pi_{\text{old}}(a | s)}{\pi_{\text{new}}(a | s)} \right] \quad (7)$$

Here π_{old} is the policy that generated the rollout, whereas π_{new} is the updated actor network; the expectation is taken over the mini-batch of actions a sampled from the stored trajectories. In short, KL divergence is tracked to quantify how far each new policy deviates from the previous one. The graph marks that all recorded values fall well below 8×10^{-3} and quickly settle around 10^{-4} , far under the soft trust-region threshold of 0.01 that would trigger early stopping in standard PPO. The vanishing divergence confirms that successive policies differ only infinitesimally, meaning updates remain inside the intended trust region and the learning process is numerically stable throughout.

This initial implementation is intentionally modest in scope. There was only one trace, one hyper-parameter setting, and a single training seed used, yet showing the PPO-LSTM agent can achieve almost perfect selection accuracy (around 99 %) within a few hundred updates. That level of sample efficiency, together with the smooth convergence diagnostics (stable KL, collapsing actor loss, orderly entropy decay), confirms that the algorithm can exploit the deterministic trajectory context characteristic

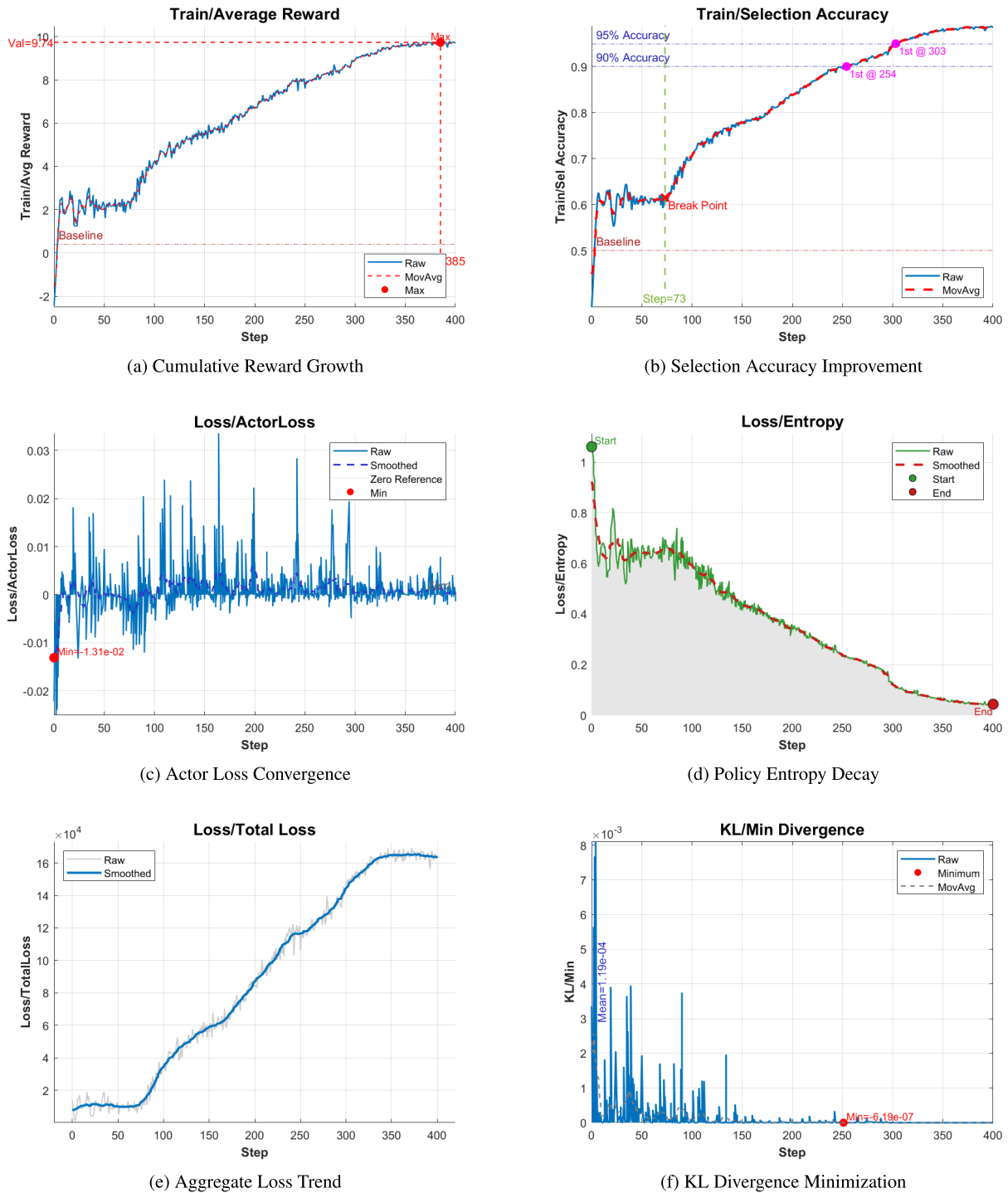


FIGURE 17. Reinforcement learning training dynamics.

of Scenario I. Of course, a full validation campaign will require richer aeronautical KPI logs, sensitivity sweeps over network depth and clip range, and stress-tests under adversarial link outages; however, the present proof-of-concept already clears the key technical risks by demonstrating that:

- LSTM memory is sufficient to capture the multi-second channel trends;

- PPO's clipped updates keep learning stable even under the aggressive reward scale.

Taken together, the results provide concrete, data-driven support for adopting a PPO-LSTM architecture as the core decision module for Scenario I.

V. INSIGHTS AND FUTURE DIRECTIONS

This paper has traced the evolution of aeronautical communications from today's links to tomorrow's predictive,

multi-bearer ATN/IPS networks. By consolidating more than 150 standards, research papers, and flight-test reports, this paper clarified the performance envelope of every major candidate link (VDL-M2, LDACS, AeroMACS, 5G/6G A2G, SB-VHF, GEO/LEO SATCOM, HF DL) and mapped them against ICAO RCP/RSP targets. Three systemic gaps were identified—reactive link choice, ignorance of airframe shadowing, and lack of route awareness—and a dual-tier on-board orchestrator was proposed to close them by fusing flight plan, attitude, and live KPI telemetry. Twelve decision-making algorithms were benchmarked under two representative flight scenarios, showing that a slow, trajectory-aware planner must be backed by an ultra-fast reactive fallback to meet link selection deadlines. The review highlights several directions where focused investigation is still required:

- 1) Preliminary simulations demonstrate that a single-layer, 128-unit LSTM feeding a clipped PPO actor–critic reaches approximately 99% link-selection accuracy and a mean per-step reward of +9.7 (97% of the ± 10 optimum) within just 400 policy updates. This confirms that LSTM’s gated memory is sufficient to encode multi-second channel trends tied to a known 4-D flight plan, and that the likelihood-ratio constraint ($\epsilon = 0.15$) yields high sample-efficiency and numerically stable learning under an aggressive reward scale. Going forward, effort should focus on enriching this same LSTM–PPO backbone with deeper or bidirectional recurrent stacks, attention layers, expanded context windows, and hyperparameter tuning to lengthen its predictive horizon.
- 2) The LTE drive-test corpus used in the proof-of-concept cannot reproduce antenna shadowing and coordinated satellite handovers, thus progress now hinges on building physics-accurate, hardware-in-the-loop digital twins that couple a 6-DoF flight simulator, ray-traced RF engine, and full network-stack emulation. Such an environment would emit labelled KPI streams (RSRP, RSRQ, SNR, latency, packet-loss) under controlled bank-angle, pitch, and route perturbations. Moreover, this could include domain-randomise weather, traffic load, and interference to expose learning agents to realistic distribution shifts to further improve the quality of the data. Lastly, such environment could provide both supervised predictors and on-policy RL algorithms with flight-representative experience long before costly flight trials, thereby closing the sim-to-real gap.
- 3) The two test cases evaluated here capture the extremes of predictability versus volatility, yet real-world operations span a richer spectrum that the orchestrator must master. With the dual-layer architecture approach (a slow flight-plan planner backed by a fast reactive fall-back), future work should introduce additional, finely graded scenarios that stress each layer in isolation and in concert. Such scenario examples are dense terminal-area arrivals with overlapping coverage

footprints and severe VDL-M2 congestion, trans-polar routes with ionospheric scintillation and sparse LEO visibility, prolonged SATCOM outages during solar storms and many more.

- 4) Standardizing the use of AI in aviation remains one of the field’s most challenging milestones. Although techniques such as contextual bandits and neuro-fuzzy hybrids have shown strong technical promise, their certification within the current regulatory envelopes of DO-178C/ED-12C [122] and European Union Aviation Safety Agency (EASA) AI Roadmap [147] are still newly outlined and detailed compliance means of verification remain an open research topic and demand further investigation.

VI. CONCLUSION

This study provided an end-to-end assessment of aeronautical communications, connecting the legacy ATN/OSI stack and its interrogation-driven link selection to the emerging ATN/IPS, multi-bearer future, and quantifying how an on-board, dual-layer orchestrator can maintain RCP/RSP compliance across nominal and off-nominal flight regimes. Our benchmarking across two canonical scenarios confirms a central result: no single algorithmic paradigm dominates across the operational envelope. Trajectory-aware contexts with predictable coverage favor sequence-model predictors and deep RL (e.g., LSTM/TCN, PPO), whereas reroutes, shadowing and KPI drift require microsecond decision latencies best served by contextual bandits or lightweight fuzzy controllers. A hybrid orchestration stack based on predictive planner plus ultra-fast reactive fallback is the only robust design pattern for next-generation airborne link management. From a literature standpoint, the review consolidated more than 140 standards and studies and maps today’s and tomorrow’s bearers such as VDL-M2, LDACS, AeroMACS, HF DL, SB-VHF, GEO/LEO SATCOM, and 5G/6G A2G against ICAO PBCS targets. The evidence base converges on three structural gaps: (1) reactive, priority link choice; (2) insufficient treatment of airframe shadowing and maneuver-induced degradations; and (3) lack of route awareness in link-management logic. These gaps are repeatedly surfaced across surveys of future aerial communications, AANETs, bearer-specific comparisons, and machine-learning-enabled networking, all of which argue for a heterogeneous, policy-driven fabric rather than a single “silver bullet” link. This synthesis directly motivates an on-board orchestrator that fuses flight plan, attitude, and live KPI telemetry to enable make-before-break horizontal handovers, especially in ORP airspace where sparse coverage magnifies the cost of reactive switching. Methodologically, our comparative analysis shows that supervised sequence learners and PPO-based agents can exploit deterministic trajectory context to anticipate fades and schedule planned handovers with high accuracy under Scenario I, as evidenced by the PPO–LSTM proof-of-concept achieving 99% selection accuracy with stable convergence diagnostics. In contrast, Scenario II imposes sub 100 ms

reaction budgets under fast KPI drift; here, contextual bandits and compact fuzzy controllers consistently meet timing with minimal compute and no offline data. The implication is clear: the orchestrator must separate concerns—slow, route-aware prediction for planned handovers; fast, rule/bandit logic for last-moment rescues—implemented as a certifiable ULCS/CM extension inside ATN/IPS to minimize LRU impact while leveraging IP-grade security. Standards and architectural alignment further strengthen the case for deployment. ATN/IPS streamlines headers, externalizes mobility via Mobile IPv6/NEMO, and adopts IKEv2/IPsec and TLS, allowing the orchestrator to focus purely on KPI sensing and decisioning rather than transport plumbing. This enables DSCP-based policy routing, cross-layer KPI fusion at ULCS, and deterministic, make-before-break triggers to anticipate a low-latency control loop that is both certifiable and software-centric. In parallel, concepts such as Hyper-Connected ATM and SB-VHF illustrate viable pathways to expand capacity and coverage via secure overlays and space-relayed VHF without wholesale avionics replacement, further increasing the value of an on-board policy engine that arbitrates among terrestrial and non-terrestrial paths.

Relative to prior work, this paper delivers four concrete advances: (1) a unified review that couples system-of-systems bearers with ATN/OSI→ATN/IPS migration and PBCS performance framing; (2) explicit problem statements and evidence for the three systemic gaps (reactivity, shadowing, route unawareness) with an implementation-ready orchestrator placement at ULCS/CM; (3) a rigorous, scenario-based algorithmic comparison showing why a dual-layer stack is necessary and how to allocate methods to layers (supervised/PPO for planned handover; bandits/fuzzy for reactive switching); and (4) an initial PPO-LSTM proof-point that de-risks the predictive layer by achieving near-perfect selection accuracy with stable KL and loss traces on realistic mobility traces serving as trajectory proxies. Collectively, these outcomes convert the orchestrator from a conceptual desideratum into an actionable architecture with performance, certification, and integration arguments aligned to current standards. To operationalize this blueprint, future work should build a flight-representative digital-twin testbed (6-DoF platform + ray-traced RF + full network stack) to generate labeled KPI streams under bank/attitude/route perturbations; extend the PPO-LSTM layer with attention/bidirectionality and conduct sensitivity sweeps over clip ranges and horizons; harden the reactive layer via context-aware bandits and compact neuro-fuzzy hybrids with formal timing guarantees; and validate ULCS/CM integration paths and safety cases against DO-178C/EASA AI guidance. Scenario coverage should expand to terminal-area congestion, polar scintillation, and solar-storm SATCOM outages to stress the two layers in isolation and jointly. These steps will close the sim-to-real gap and provide the certification-grade evidence needed for airline and ANSP adoption.

LIST OF ACRONYMS AND ABBREVIATIONS

3GPP	3rd Generation Partnership Project.
4-D	Four-Dimensional.
4G	Fourth-Generation Mobile Network.
5G	Fifth-Generation Mobile Network.
6G	Sixth-Generation Mobile Network.
A2A	Air-to-Air.
A2C	Advantage Actor-Critic.
A2G	Air-to-Ground.
A2SAT	Air-to-Satellite.
AANET	Aeronautical Ad-hoc Network.
AAS	Active Antenna System.
ACARS	Aircraft Communications Addressing and Reporting System.
ACD	Aircraft Control Domain.
ACL	ATC Clearances.
ACM	ATC Communications Management.
ADS-B	Automatic Dependent Surveillance–Broadcast.
ADS-C	Automatic Dependent Surveillance–Contract.
AFDX	Avionics Full-Duplex Switched Ethernet.
AHP	Analytic Hierarchy Process.
AI	Artificial Intelligence.
A-ID	ATS Interfacility Data Communication.
AIDC	ATS Interfacility Data Communication.
AM(R)SS	Aeronautical Mobile-Satellite (Route) Service.
AMC	ATC Microphone Check.
AMHS	ATS Message Handling Services.
AMSS	Aeronautical Mobile Satellite Service.
ANASTASIA	Airborne New Advanced Satellite Techniques & Technologies in a System Integrated Approach.
ANDSF	Access Network Discovery and Selection Function.
ANDSF-HO	Access Network Discovery and Selection Function – Handover.
ANFIS	Adaptive Neuro-Fuzzy Inference System.
ANSP	Air Navigation Service Provider.
AOC	Airline Operational Control.
AP	Access Point.
APAC	Asia–Pacific.
APIM	ARINC Project Initiation/Modification.
APNT	Alternative Positioning, Navigation, and Timing.
ARINC	Aeronautical Radio, Incorporated.
ARINC-653	Avionics Application Standard Software Interface (specification 653).
ARNS	Aeronautical Radionavigation Service.
ATC	Air Traffic Control.
ATM	Air Traffic Management.
ATN	Aeronautical Telecommunication Network.

ATN/IPS	Aeronautical Telecommunication Network over Internet Protocol Suite.	FCI	Future Communication Infrastructure.
ATN/OSI	Aeronautical Telecommunication Network over Open Systems Interconnection.	FDD	Frequency-Division Duplex.
ATS	Air Traffic Services.	FIR	Flight Information Region.
AVLC	Aeronautical VHF Link Control.	FIS	Fuzzy Inference System.
BDU	Basic Data Unit.	FL	Flight Level.
BE	Best-Effort (service class).	FLC	Fuzzy-Logic Controller.
BER	Bit-Error Rate.	FMS	Flight Management System.
BGP-4+	Border Gateway Protocol version 4+.	GAE	Generalized Advantage Estimation.
CANSO	Civil Air Navigation Services Organization.	GAT	General Air Traffic.
CFIT	Controlled Flight Into Terrain.	GEO	Geostationary Earth Orbit.
CLNP	ConnectionLess Network Protocol.	GNN	Graph Neural Network.
CM	Context Management.	GNSS	Global Navigation Satellite System.
CMU	Communications Management Unit.	GPU	Graphics Processing Unit.
CNN	Convolutional Neural Network.	HAPS	High Altitude Platform Systems.
CNS	Communication, Navigation and Surveillance.	HAT	Hoeffding Adaptive Tree.
ConOps	Concept of Operations.	HCATM	Hyper-Connected Air Traffic Management.
CPDLC	Controller–Pilot Data Link Communications.	HDLC	High-Level Data Link Control.
CPU	Central Processing Unit.	HF	High Frequency.
CRAHN	Cognitive Radio Ad-hoc Network.	HFDL	High-Frequency Data Link.
CSC	Common Signalling Channel.	HFNPDU	High Frequency Network Protocol Data Units.
CSMA	Carrier Sense Multiple Access.	HOM	Handover Margin.
CSP	Communication Service Provider.	HT	Hoeffding Tree.
C-V2X	Cellular Vehicle-to-Everything.	I/O	Input/Output.
D8PSK	Differential 8-Phase Shift Keying.	IAAC	Improved Adaptive Ant Colony.
DAL	Design Assurance Level.	IATA	International Air Transport Association.
DAL-B/C	Design Assurance Levels B and C.	ICAO	International Civil Aviation Organization.
DCPC	Direct Controller-Pilot Communications.	ICCAIA	International Coordinating Council of Aerospace Industries Associations.
DDPG	Deep Deterministic Policy Gradient.	IDRP	Interdomain Routing Protocol.
DHNN	Discrete Hopfield Neural Network.	IEEE	Institute of Electrical and Electronics Engineers.
DL	Deep Learning.	IFEC	In-Flight Entertainment and Connectivity.
DLIC	Data Link Initiation Capability.	IFR	Instrument Flight Rules.
DoF	Degrees of Freedom.	IKEv2	Internet Key Exchange version 2.
DQN	Deep Q-Network.	IoT	Internet of Things.
DRL	Deep Reinforcement Learning.	IP	Internet Protocol.
DSBAM	Double Side-Band Amplitude Modulation.	IPS	Internet Protocol Suite.
DSCP	Differentiated Services Code Point.	IPsec	Internet Protocol Security.
DSRC	Dedicated Short-Range Communications.	IPv6	Internet Protocol version 6.
EAP	Extensible Authentication Protocol.	ISO	International Organization for Standardization.
EATMA	European Air Traffic Management Architecture.	ITU	International Telecommunication Union.
EIRP	Equivalent Isotropic Radiated Power.	ITU-R	International Telecommunication Union – Radiocommunication.
eMBB	enhanced Mobile Broadband.	KPI	Key Performance Indicator.
eNB	Evolved Node B.		
ertPS	Extended Real-Time Polling Service.		
EULAW	European Union Law.		
EUROCAE	European Organisation for Civil Aviation Equipment.		
eVTOL	electrical Vertical Take-Off and Landing.		
FACOM	Future Aerial-COMmunications.		
FANS	Future Air Navigation System.		

LBA	Link Budget Analysis.	QUIC	Quick UDP Internet Connections.
LDACS	L-band Digital Aeronautical Communications System.	RAIM	Receiver Autonomous Integrity Monitoring.
LEO	Low Earth Orbit.	RAT	Radio Access Technology.
LRUs	Line-Replaceable Units.	RCP	Required Communication Performance.
LSTM	Long Short-Term Memory.	RIS	Reconfigurable Intelligent Surface.
LTC	Local Terminal Control.	RL	Reinforcement Learning.
LTE	Long-Term Evolution.	RNAV	Area Navigation.
MAC	Media Access Control.	RNN	Recurrent Neural Network.
MDP	Markov Decision Process.	RNP	Required Navigation Performance.
MEO	Medium Earth Orbit.	ROHC	Robust Header Compression.
MIL-STD-188-110A	Military Standard 188-110A.	RPAS	Remotely Piloted Aircraft System.
ML	Machine Learning.	RSP	Required Surveillance Performance.
MLP	Multi-Layer Perceptron.	RSRP	Reference-Signal Received Power.
mMTC	massive Machine-Type Communication.	RSRQ	Reference-Signal Received Quality.
mmWave	Millimeter-wave.	RSSI	Received Signal Strength Indicator.
Mobile IP	Mobile Internet Protocol.	RTCA	Radio Technical Commission for Aeronautics.
MOPS	Minimum Operational Performance Standards.	rtPS	Real-Time Polling Service.
MOS	Mean Opinion Score.	SAGIN	Space-Air-Ground Integrated Network.
MSE	Mean Squared Error.	SARPs	Standards and Recommended Practices.
NACK	Negative Acknowledgment.	SATCOM	Satellite Communication.
NASA	National Aeronautics and Space Administration.	SBAS	Satellite-Based Augmentation System.
NEMO	Network Mobility Mobile IPv6 extension.	SB-VHF	Satellite-based Very High Frequency.
NGSO	Non-Geostationary Satellite Orbit.	SESAR	Single European Sky ATM Research.
nrtPS	Non-Real-Time Polling Service.	SESAR JU	SESAR Joint Undertaking.
NS-2	Network Simulator 2.	SITA	Société Internationale de Télécommunications Aéronautiques.
NS-3	Network Simulator 3.	SNDCF	Sub-network-Dependent Convergence Function.
NTN	Non-Terrestrial Networks.	SNR	Signal-to-Noise Ratio.
NTNs	Non-Terrestrial Networks.	SSR	Secondary Surveillance Radar.
OFDM	Orthogonal Frequency-Division Multiplexing.	SU	Secondary User.
OFDMA	Orthogonal Frequency-Division Multiple Access.	SVC	Switched Virtual Circuit.
ORP	Oceanic, Remote & Polar.	SVM	Support Vector Machine.
OSI	Open Systems Interconnection.	SWIM	System-Wide Information Management.
PAPR	Peak-to-Average Power Ratio.	TBO	Trajectory Based Operations.
PBCS	Performance-Based Communication and Surveillance.	TCAS	Traffic-Collision Avoidance System.
PDR	Packet Delivery Ratio.	TCN	Temporal Convolutional Network.
PDU	Protocol Data Unit.	TCP	Transmission Control Protocol.
PER	Packet-Error Rate.	TDMA	Time Division Multiple Access.
PKI	Public Key Infrastructure.	TLS	Transport Layer Security.
PMTU	Path Maximum Transmission Unit.	TN	Terrestrial Networks.
PPO	Proximal Policy Optimisation.	TP4	Transport Protocol Class 4.
PPO	Proximal Policy Optimization.	TTT	Time-to-Trigger.
PU	Primary User.	UAM	Urban Air Mobility.
QAM	Quadrature Amplitude Modulation.	UAS	Unmanned Aircraft System.
Q-Learning	Q-Learning.	UAV	Unmanned Aerial Vehicle.
QoS	Quality of Service.	UCB	Upper Confidence Bound.
QPSK	Quadrature Phase-Shift Keying.	UDP	User Datagram Protocol.
		UE	User Equipment.
		ULCS	Upper Layer Communication Service.
		URLLC	Ultra-Reliable Low-Latency Communication.
		U-Space	U-Space (EU framework of UTM services).
		UTM	Unmanned Aircraft System Traffic Management.

V2V	Vehicle-to-Vehicle.
VDL-M2	VHF Data Link Mode 2.
VHF	Very High Frequency.
VOICE	VHF Over LEO Constellations for Europe.
VPN	Virtual Private Network.
VSAT	Very Small Aperture Terminal.
WG	Working Group.
Wi-Fi	Wireless Fidelity.
WiMAX	Worldwide Interoperability for Microwave Access.
WLAN	Wireless Local Area Network.
WRC	World Radiocommunication Conference.
XGBoost	Extreme Gradient Boosting.

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