APPLICATIONS AND CHALLENGES FOR AIRBORNE AD-HOC COMMUNICATION NETWORKS IN ORP AIRSPACES USING THE L-BAND

Tobias Marks[1], Alexander Hillebrecht[1] & Miguel A. Bellido-Manganell[2]

[1]German Aerospace Center, Institute of Air Transport, Hamburg, Germany
[2]German Aerospace Center (DLR), Institute for Communication and Navigation, Weßling, Germany

Abstract

Data communication is an essential part of today's air traffic operations, enabling more flexible routing of aircraft leading to increased airspace capacity. While older generations of data link technology approach their technological limits, new technologies and approaches are being developed. Beside satellite communication and high frequency radio, one approach to enable data communication in remote, polar and oceanic airspaces such as the North Atlantic, is the establishment of aeronautical ad-hoc networks (AANETs). Such networks are built up by direct data links between the aircraft which are acting as communication nodes, while ground connectivity is provided through dedicated gateway aircraft that are connected to ground stations or satellites. The establishment of AANETs enables new procedures and applications and provides a backup to existing communication infrastructure, resulting in technological and operational requirements and constraints. As the AANET performance is strongly influenced by the current air traffic situation, it is essential to understand these requirements in order to properly design the systems. In our work we analyze applications enabled by AANETs and identify challenges for the design and development of the communication technology.

Keywords: ad-hoc networks; data link; communication

Abbreviations

A/A air-to-air
A/G air-to-ground
AAC Airline Administrative Control
AANET Aeronautical Ad-hoc Network
AAR Aircraft Aerial Refuelling
ADS-B Automatic Dependent Surveillance - Broadcast
ADS-C Automatic Dependent Surveillance - Contract
AOC Aeronautical Operational Control
APC Aeronautical Passenger Communication
APNT Alternative Positioning, Navigation and Timing
AS Airborne Station
ATC Air Traffic Control
ATCO Air Traffic Control Operator
ATM Air Traffic Management
ATS Air Traffic Services
ATSU Air Traffic Service Unit
AWSE Aircraft Wake Surfing for Efficiency
CAT Clear Air Turbulence
CVR Cockpit Voice Recorder
CPDLC Controller–Pilot Data Link Communication

DCPC Direct Controller–Pilot Communications
DME Distance Measuring Equipment
FDR Flight Data Recorder
FRA Free Route Airspace
G/G ground-to-ground
GS Ground Station
HF High Frequency
ICAO International Civil Aviation Organization
ITU International Telecommunication Union
LDACS L-band Digital Aeronautical Communications System
LEO Low Earth Orbit
LRCS Long Range Communication System
MAC Medium Access Control
MSPSR Multi-Static Primary Surveillance Radar
NAT North Atlantic
NATS North Atlantic Track System
NRA Non-Radar Airspaces
OBB Online Black Box
ORP Oceanic, Remote, Polar
OTS Organized Track System
PACOTS Pacific Organized Track System
RFI Radio Frequency Interference
SATCOM Satellite Communication
TBO Trajectory Based Operations
TCAS Traffic Alert and Collision Avoidance System
TACAN Tactical Air Navigation System
VHF Very High Frequency

1. Introduction

Several oceanic remote and polar (ORP) airspaces e.g. the North Atlantic or the North Pacific accommodate very high air traffic volumes, that are expected to further increase in the future. However, a significant and limiting drawback of these airspaces is the lack of radar coverage. Hence, in order to use these airspaces efficiently, the North Atlantic Track System (NATS) and the Pacific Organised Track System (PACOTS) were established separating air traffic flows both by assigning flights to dedicated tracks and by assuring time based separation within the tracks. Here, for many years air traffic control (ATC) relied on HF voice communication and considerable large separations between aircraft to ensure safe operations. This system currently seems to come to an end as enhanced surveillance enabled by ADS-B, whose messages are also relayed via satellite links to the ATC entities, provides increased situational awareness for ATC leading to reduced separations (1) and might even enable free routing of flights in these airspaces in the future (2). Other surveillance technologies like multilateration over satellite are at the horizon (3).

However, beside the lack of radar coverage, another considerable drawback in ORP airspaces is the fact, that data communication is only possible via satellite links (4). Apart from the low bandwitdth HF data link and its very limited capacity, direct air-to-ground (A/G) links are not available. These satellite links, however, can exhibit considerable high latencies depending on the system used (5) and can be expected to be costly as they are generally operated by private companies (e.g. Starlink (6), Iridium, etc.). Although governmentally owned systems might be available in the future (7), the upcoming satellite mega constellations (Starlink, OneWeb, LeoSat, TeleSat, CASC Honyan and others) might create future risks to low earth orbit (LEO) as well as to the atmosphere (8) and future international conflicts might question the availability of the systems (9). Hence, the required service quality and availability might not be guaranteed.

Therefore, the establishment of aeronautical ad-hoc communication networks (AANETs) between aircraft using direct air-to-air (A/A) data links yields another opportunity to provide communication in these airspaces. It would additionally enable a set of new use cases that can lead to a more efficient and safer airspace use while at the same time acting as a backup system in the case that the primary communications channel is not functional or has a reduced availability.

As an example, satellite links are strongly affected by antenna misalignment and outages can arise during aircraft maneuvers such as banking. Although such maneuvers also lead to signal power fading in the A/A links (10), the lower distance between aircraft leads to a lower dependency on the antenna alignment in the A/A case.

As a consequence, in this work we identify and describe a set of possible applications for aeronautical ad-hoc communication networks in ORP regions and derive resulting requirements from them based on operational constraints. Furthermore, we will identify technical constraints by using the L-Band for building up the radio connections. This will help the future development of AANET technology and systems and the assessment of AANET performance in real world scenarios.

2. Related work

The idea of using AANETs in ORP regions is not new (see e.g. (11), (12), (13) or (14)). Several works deal with the so called *Airborne Internet* or *Internet above the Sky* (see e.g. (15), (16) and (17)) that is envisioned to provide high bandwidth data link for Aeronautical Passenger Communication (APC) through an ad-hoc network in between aircraft.

Due to the complexity of the system, there are numerous technical challenges in designing such AANETs. Zhang et al. (18) give a general systematic overview of use cases, requirements and challenges imposed by the implementation of AANETs. Kumar et al. (19) identify future challenges from the viewpoint of the OSI network model. A general holistic overview over open challenges of AANETs is given by Bilen et al. (20).

In (21), the authors discuss the challenges in the design of an A/A data communications system and the different design options. The authors in (10) analyse A/A channel measurements and obtain the main characteristics of the A/A channel that shall be considered for the design of the A/A data link. In (22), the expected air traffic density in Europe is analysed and the performance of multiple MAC protocols is compared in such air traffic conditions. An analysis on the usability of the L-Band for the AANET is presented in (23), where the compatibility of the AANET with the legacy systems is addressed.

However, an overview of the applications enabled by the AANET in ORP airspaces along with the resulting challenges is not known by the authors. In this paper, therefore, an overview of applications is presented and challenges resulting from operational or technological perspective are identified.

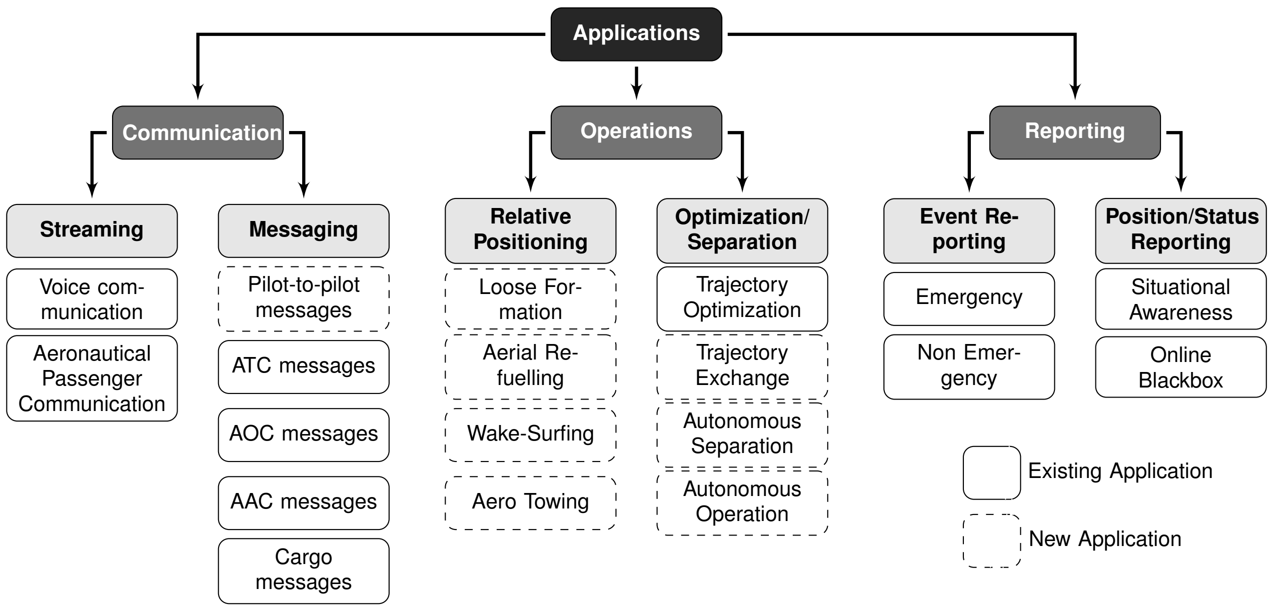

Figure 1 – Structured overview of AANET applications

3. General Assumptions

The AANET as analysed in this paper is intended to be established between *civil aircraft* of commercial air transport. In addition, the network might also be applied to state aircraft depending on their intended use and the specific use case. We do not consider the application of the AANET in the military domain.
Additionally, it is assumed that the AANET is primarily intended to be used in *ORP airspaces* and is not intended to replace or complement existing systems in the continental domain.
Furthermore, it is assumed that if a destination is not within transmission radius of the data link, data packets have to be forwarded via *aircraft-relays* until the destination can be reached. Several hops might have to be used for a data message to reach its final destination.
The works presented in this paper are results from the project IntAirNet (Inter Aircraft Network) that was funded by the German Ministry of Economic Affairs and Climate Action (grant agreement no. 20V1708B) and analysed the development of an A/A data link based on the L-band Digital Aeronautical Communications System (LDACS) technology.
LDACS is a new air-to-ground (A/G) communications system that shall operate in the aeronautical L-band and provide secure data links between aircraft and ground stations in order to support ATS and AOC data traffic. LDACS is reaching a high maturity level and is close to its standardization by the International Civil Aviation Organization (ICAO). It has already been demonstrated and its capabilities have been assessed in flight campaigns (see (24)). Accordingly, for this work it is further assumed that the AANET is operating in the L-Band.

Based on these general assumptions and boundary conditions, potential baseline services for AANETs will be presented in section 4, followed by an overview of the applications. The applications presented are neither prioritized nor following a specific order and the list is non-exhaustive. Nevertheless it should give an overview of possibilities enabled by such a system. Some communication systems (e.g. satellite communication) already enable various applications (Existing Applications, see section 5), hence the AANET can act as a backup or complementary system. Other use cases are enabled by the AANET in the first place (New Applications, see section 6). Figure 1 shows a structured overview of the AANET applications and Table 1 lists the applications and indicates the basic requirements. All applications will be presented in more detail in the sections below.

4. Base Services

In this section, base services are presented that are favourable to be provided by the data link system.

4.1 Time Synchronization

Correct time synchronization within the AANET should be independent of satellite based systems, such as GNSS, in the event of an outage of such systems. Although a high accuracy clock (e.g. atomic clock) can be installed in the airborne radio to maintain a certain level of synchronization during short-term GNSS outages, the time will degrade continuously until a new synchronization reference is found. This time reference could be acquired from an alternative positioning, navigation and time (APNT) system. For example, LDACS is intended to also provide a GNSS-independent APNT solution, which might however be only available in the continental airspace where the ground stations are available. In ORP regions, if no APNT solution is available, the AANET might have to find a way to time synchronize with other aircraft either locally or by using the time reference of other airborne stations with an accurate and available time reference source (e.g. GNSS or an APNT system).

4.2 Frequency Synchronization

Same as the time synchronization, frequency synchronization within the AANET must be achievable without the need of satellite based systems such as GNSS. In case of a GNSS outage, the same strategy followed for time synchronization can be employed. A local frequency synchronization can be agreed up with the other airborne stations of the AANET, or an absolute frequency reference can be achieved through an APNT, if available. Correct frequency synchronization in the AANET against common absolute frequency normals might be helpful for higher-layer services, i.e. time synchronization, range, position, formation flight, etc.

4.3 Ranging

Airborne stations shall be able to determine the distance between each other. There are multiple methods to achieve this, including active and passive methods. Active methods entail cooperation between the aircraft in the form of requests and responses with known processing and access timings. Passive methods profit from the knowledge of certain characteristics of the transmissions to derive the ranges. In general, these methods require either time or frequency synchronization, or both.

4.4 Positioning

An airborne station shall be able to determine its position. Although the primary means for this might be GNSS, aircraft shall also be able to know their position during GNSS outages. The position can be derived from the position of other aircraft, ground stations, or derived from an APNT system.

5. Existing Applications

In this section, we discuss the applications that are already in use and supported by other communication systems. For these applications, the AANET can provide redundancy in case of system failures.

5.1 Aeronautical Passenger Communications

Aeronautical passenger communication (APC) entails communication related to non-safety voice and data services to passengers and crew members for personal communications. Passengers more and more expect permanent connectivity to common internet services (e.g. email, WWW, VoIP, video telephony, video/audio streaming) during flight.

APC might require high *bandwidth* and/or low *latencies* depending on the specific application. As APC communication has low priority as it is not safety critical, the AANET should provide *prioritization*. Also APC communication is subject to significant changes in terms of bandwidth demand and APC service usage in comparison with ATS or AOC data communication, with initial implementation considerations assessing an available data rate per passenger of 256 kbps as sufficient (25), while more recent works aim to enable data rates of up to 10 Mbps (26).

For APC, an AANET needs to provide relay functionality while data storage is not mandatory. APC messages or data streams can be assumed to be low priority.

5.2 Voice Communications

Direct Controller-Pilot Communications (DCPC) in ORP airspaces currently relies on HF voice communication as basic means of communication (27), with voice over satellite (SATVOICE) being an established, commonly used alternative (28). In the near future, SATVOICE (29) will be a sufficient means of communication in ORP airspace (30) with HF voice communication being phased out in the long term (31). However, if in crowded airspaces, such as the North Atlantic, satellite communication is disturbed for any reason (e.g. space weather (32), technical failures) a second long range communication system (LRCS) for DCPC is mandatory. Here, the AANET can act as a backup channel.

However, voice communication requires low latencies. Depending on the structure of the AANET, a significant amount of hops might be needed in order to establish a connection. The required communication performance for aeronautical SATVOICE is allowing latencies of up to 400 s for one mutual DCPC message exchange (29), therefore, the higher latencies in the AANET case might still be feasible.

Depending on the actual implementation, the AANET needs to provide relay functionality and data storage. In the case of direct voice communication (full duplex) the data traffic might need to be prioritized in order to meet latency requirements. To overcome latency issues, asynchronous communication using a mailbox-type of systems could be used.

5.3 Events Dissemination

This application covers the communication of information regarding single events to one or more recipients within the AANET or to ground entities. Depending on the actual message type, the AANET needs to provide relay functionality, data storage and prioritization (e.g. for ATS or emergency messages).

5.3.1 Emergencies

The types of emergencies that an aircraft can encounter during flight are manifold. In general, if an emergency occurs, ATC must be contacted and asked for advice (33) and checklists need to be followed. If a contact to ATC cannot be established, pilots have to take action themselves and inform surrounding traffic of their position and intentions. The A/A data link can be used to send the particular messages to surrounding traffic with a possible wider range via message forwarding than existing ADS-B / Mode-S solutions.

5.3.2 Non-Emergencies

Especially in the context of increasing clear air turbulence (CAT) e.g. over the North Atlantic (34), the AANET can be used to communicate safety-relevant weather events like CAT, wind, thunderstorms, weather radar data, icing regions, and more to airplanes operating in the same airspace or flying on or close to the own track. Other aircraft can then react to the specific weather information and adjust their flight level or trajectory in accordance with ATC. This can result in a safer and more efficient operation of the aircraft.

5.4 Situational Awareness

The situational awareness within non-radar airspaces used to be limited to ADS-C for a long time until, some years ago, the use of satellites to receive ADS-B data was first proven by DLR and ESA (see e.g. (35) or (36)). Since March 2019, a system operated by the company Aireon is in service using Iridium Next satellites to globally receive ADS-B data on a regular basis. This enhanced real-time surveillance capability already led to a drastic reduction of separation standards on the North Atlantic (1) and might potentially make the OTS obsolete in the future (2).

The A/A data link can be used to transmit the ADS-B data more efficiently than the currently available solutions and to prevent the congestion of the 1090 MHz. In addition, in case of an outage of the satellite system receiving the ADS-B data, the AANET can be used to propagate the data to other network members, such as ATC ground entities. Thus, it can serve as a backup system to forward ADS messages. Each network member receiving the ADS-B data, such as an aircraft, can use it to generate an overview of the air traffic situation around it.

Another drawback of the current systems is the dependency of ADS-B on GNSS. More precisely, in case of a GNSS outage (e.g. caused by space weather (32) or radio frequency interference (37), (38)), ADS-B cannot be provided (39). In this case, the ranging and positioning capabilities of the AANET might be used to maintain situational awareness on ground and in the air (see section 4).

For the situational awareness the AANET needs to provide relay functionality and should support broadcast or geocast communications.

5.5 Online Black Box

An online black box (OBB) can be considered a flight data recorder (FDR) or cockpit voice recorder (CVR) that allows wireless transmission of safety-critical data to a sink outside the aircraft in case of an emergency. Flight data can be sent directly to a sink located on ground (e.g. authorities, airline) or in case that a ground connection is not available, it can be forwarded via an available indirect link e.g. via a satellite network or an AANET. The data transmission can be triggered in case of an emergency or being a continuous or periodic transmission of safety-critical flight data. (40) gives a good overview of triggered data transmission and the feasibility and necessity of such systems. However, shortcomings of the OBB using SATCOM such as screening effects by the fuselage or wings are pointed out. Current developments in avionics (see e.g. (41)) also show the interest of the industry in such systems. An AANET would provide some advantages for this particular use case. The FDR and CVR data can be routed through the network until a ground station becomes reachable.

Alternatively the data could be temporarily buffered on a nearby aircraft until that aircraft can forward it to a ground station or download it at the airport after landing. In both cases the data is not lost and can be used to quickly initiate search and rescue missions and analyse the accident.
The requirements for a FDR or CVR are defined in (42). The AANET needs to provide relay functionality, data storage and prioritization.

5.6 Addressed Messaging

This set of use cases covers the transmission of simple text messages between aircraft and between aircraft and ground entities. In this particular set of applications the AANET could be used as an alternative to costly SATCOM connections and can provide for a backup system, which is of particular interest in the ATS case. Depending on the actual message type, the AANET needs to provide relay functionality, data storage and prioritization (e.g. to prioritize ATS messages over other types of messages).

5.6.1 Air Traffic Services

Air Traffic Services (ATS) communication covers communication between the aircraft and ground in order to ensure a safe conduction of the flight. Aircraft send real-time ATC data (e.g. clearance requests) to the corresponding Air Traffic Service Unit (ATSU) using Controller Pilot Data Link Communication (CPDLC). As ATS communication is safety and time critical, a prioritization over other types of messages is required. Data link requirements for ATS communication can be found in ICAO Doc 10037, “Global Operational Data Link (GOLD)" (43). Special requirements for data link services in ORP airspaces are defined in ED-122 (44) from EUROCAE.

5.6.2 Aircraft Operational and Administrative Control

Aircraft Operational Control (AOC) covers communication between an airline and its aircraft. Relevant information can be maintenance data, adaptions to flight plan, status updates, weather updates etc. The actual set of AOC applications in use is differing between airlines and aircraft types. Unfortunately only scarce information is publicly available on the actual application sets used and usually generalized application sets such as (45) are taken as a basis for technology assessment.
Aircraft Administrative Control (AAC) is addressing purposes such as flight and ground transportation bookings, crew or aircraft deployments and other logistical purposes that maintain or enhance the efficiency of overall flight operation (46). The data link system can be used to react to delay concerning the connecting flights of the passengers and substitutes can be planned long beforehand.

5.6.3 Cargo Communication

Several types of cargo e.g. perishables, pharmaceuticals, sensible cargo (e.g. explosives) or live animals need real-time monitoring of e.g. position, temperature, humidity, tilt angle, shocks and more. Those cargo constitute a big part of today’s airfreight (47). Currently the data that is acquired in the cargo containers can only be downloaded after landing. (47) shows, that there is a need from logistics companies to enable traceability and continuous data-exchange along the whole supply chain in order to improve the real time visibility, trigger subsequent/replacement delivery or optimize processes.

5.7 Trajectory Optimization

While being constrained to an organized track system (OTS), like e.g. on the North Atlantic, opportunities to optimize flight tracks are very limited. In the context of trajectory based operations (TBO) and Free Route Airspaces (FRA) 4D-Trajectories optimized to a specific target function (such as time, cost or fuel consumption) can be dynamically estimated by ATM entities, airlines or aircraft and distributed among all stakeholders via data link. This can enable optimal routing in the ORP region in the future (e.g. (48) or (49)) and can for example reduce fuel consumption (50), flight times or climate cost (51).

6. New Applications

This section covers new applications that are enabled by a A/A data link in the first place.

6.1 Pilot-to-pilot Message

This application allows a quick exchange of short text-based information between aircraft (see also section 5.6). The messages can be expected to be limited in size and shall allow fast and easy message issuing (SMS alike) for the pilots.

6.2 Optimization and Separation

The establishment of an AANET bears the potential to further optimize air traffic and eventually enable autonomous separation.

6.2.1 4D-Trajectory Exchange

Aircraft can directly exchange their 4D-Trajectories with other aircraft and thereby, if necessary, resolve potential conflicts. In both cases, the AANET system should support broadcast and unicast routing. A service setup similar to 4DTRAD (52) from CPDLC can be used.

6.2.2 Autonomous Separation and Flight

Aircraft Autonomous Separation Assurance (ASAS) moves the responsibility to maintain proper separation from ATC to the pilots. Aircraft are aware of the IDs, positions and trajectories of other aircraft and are capable of resolving conflicts by themselves via coordination of separation maneuvers. This way, they can self-separate from other aircraft without any external support from ATC. This application is, therefore, strongly related to the exchange of trajectories. Additionally autonomous separation can be considered to be the enabler for autonomous operation and provide new perspectives on the implementation of autonomous in-trail procedures, which are currently thought to be based on ADS-B (53). This application can strongly benefit from a direct A/A data link allowing the aircraft to directly communicate to each other.

6.3 Relative Positioning

Closely related to the self separation application the ability to position a group of aircraft relative to each other opens up a whole set of new applications.

In general all these applications require the exchange of position and speed data to establish and maintain the relative positions (e.g. using modified ADS-B or TCAS systems). If in the group only one aircraft maintains contact to ATC also the CPDLC data need to be handed over to the other participants. In the case of aerial refuelling (AAR) and aircraft wake surfing for efficiency (AWSE) also data concerning the wind conditions need to be transferred. In the AWSE case additionally maneuvers need to be commanded from the leader to the follower to allow for simultaneous course adaptions or step climbs.

6.3.1 Loose Formation Flight

A so called loose formation flight (LFF) is established when several aircraft are grouped together (54) without using the benefits provided by other aircraft wake vortices. The positions and separation within the formation are maintained by the formation members by exchanging positional and flight data. The coordination of the group is executed by a distinct formation leader that is determined upon formation build-up. This formation leader maintains contact to ATC and communicates instructions to the whole formation. The benefit of LFF can be an increased airspace capacity and reduced ATCO workload (55) as well as a possible reduction or sharing of ATC fees for air traffic participants.

6.3.2 Wake Energy Harvesting

Wake energy harvesting, aircraft wake surfing for efficiency (AWSE) or aerodynamic formation flight (see e.g. (56)) is established when a following aircraft is using the up-wash of a leading aircraft's wake in order to save energy. The positions and separation within the formation are maintained by the formation members by exchanging positional and flight data. It is essential and safety critical that the follower maintains the correct position in the leaders wake. In a formation the coordination of the group is executed by the leader. This formation leader maintains contact to ATC and communicates instructions to the follower. As wake energy harvesting is a promising concept to reduce climate impact of aviation (see (57), (58)) it is a promising use case for AANET-based applications. Hence, aircraft manufacturers, ANSPs and research institutes followed this idea (e.g. (59) and (60)) and AWSE is also a solution in the current SESAR 3 JU programme (61).

6.3.3 Air-to-Air Refuelling

Air-to-air refuelling (AAR) is a long-standing, established practice in military aviation and can be envisioned for commercial air transport as well promising significant fuel savings (62). Here, one receiver aircraft is refuelled by a tanker aircraft while airborne. The receiver can, therefore, extend it's range or carry less fuel leading to energy savings caused by the so called fuel-for-fuel effect. In the project RECREATE (see e.g. (63)) a feeder cruiser concept was evaluated including AAR. The connection maneuver of the two airplanes is difficult and it can be supposed that in order to establish it as a standard procedure in commercial aviation, a high degree of automation is needed. This high degree of automation in turn requires a stable data link connection between the tanker and the receiver to exchange flight and positional data.

6.3.4 Aero Towing

The concept of aero towing is known since the early beginnings of aviation from military gliders or sailplanes being towed to altitude by a motorized craft. The modern implementation of this concept sees an electric aircraft connecting to a fully automated electric tug in mid-air and being towed towards its destination. After the energy of the tug is depleted, it lands at an intermediate airport and another tug takes over. Recently the concept was adopted by Magpie Aviation (64) performing tests of connecting planes in mid-air. Same as AAR and AWSE this concept would benefit from a stable data link in between aircraft.

Table 1 – Overview of applications for A/A data link and general requirements. (x = applicable / (x) = depending on actual implementation)

Use case	A/G	A/A	Backup	Enabler	broadcast	unicast	relay	storage	prioritization
Voice com.	x	x	x	-	-	x	x	(x)	(x)
APC	x	-	x	-	-	x	x	-	-
Addr. msg. P2P	-	x	-	x	-	x	x	x	-
Addr. msg. ATS	x	-	x	-	-	x	x	x	x
Addr. msg. AOC/AAC	x	-	x	-	-	x	x	x	(x)
Addr. msg. Cargo	x	-	x	-	-	x	x	x	(x)
Situational awareness	x	x	-	-	x	-	x	-	-
Online blackbox	x	x	x	-	-	-	x	x	x
Events rep. Emergency	x	x	x	x	x	-	x	x	x
Events rep. Non-Emergency	-	x	-	x	x	-	x	x	-
Optimization of 4D traj.	x	-	-	-	-	x	x	-	-
Exchange of flight plan	-	x	-	-	-	x	-	-	-
Self-separation	-	x	-	x	x	-	-	-	(x)
Loose formation flight	-	x	-	x	-	x	-	-	(x)
Wake Surfing	-	x	-	x	-	x	-	-	(x)
Aerial Refuelling	-	x	-	x	-	x	-	-	(x)
Aero Towing	-	x	-	x	-	x	-	-	(x)

7. Requirements and Challenges

7.1 General Requirements from Applications

Beside the special requirements each application might pose on the data link, a set of general requirements for the AANET can be defined. Table 1 gives an overview of the single applications and these requirements.

7.1.1 Prioritization

Some messages, such as emergency or ATC messages, might need to be handled with priority over other types of messages, such as APC messages. Therefore, the A/A data link must provide prioritization means to the application's data. This is already provided by other aeronautical systems such as LDACS A/G as demonstrated in flight trials in (24).

7.1.2 Relay Function

In general aircraft need to be able to relay data from one node to another node, without processing the application data themselves.

7.1.3 Data Storage

If data cannot be forwarded through the network to its final destination due to connectivity issues, it is necessary to store the data locally until it can be handed over to the next node. This is particularly important for the OBB use case.

7.1.4 Routing Schemes

Different routing schemes need to be provided depending on the application. In the case of direct messaging, unicast is sufficient. In the case of situational awareness, geocast or broadcast functionality needs to be provided. Depending of the application, also multicast communications might need to be supported by the AANET.

7.2 Operational Requirements and Challenges

The performance of an ad-hoc network strongly depends on the number of nodes and their distribution in space. In the special case of the AANET, the nodes are moving at high relative speeds, which results in additional technological and operational requirements. The following requirements and challenges result from operational assessments as presented in (65) and (66).

7.2.1 Available Aircraft

Air traffic density fluctuates drastically throughout a day. For example, the flight traffic on the North Atlantic occurs in two opposite, wave-like traffic flows (27). Here, especially in the beginning and at the end of each wave, aircraft density and, hence, connectivity, can be expected to decrease.

7.2.2 Equipped Aircraft

Not all aircraft can be expected to be equipped with the new communication system right from the beginning. Especially during the introduction of the new system the performance will be drastically reduced compared to a state in which the system is well established. In (66) and (65), possible pathways to introduce the new system are indicated.

7.2.3 Communication Range

In order to provide noteworthy connectivity, a minimum radio communications range of the data link is required. In (67), a range of 100 NMi or 150 NMi is assumed based on initial technology assessments, while (68) define a maximum range of 200 NMi. In (66), a range of more than 135 NMi was recommended to avoid high data rate peaks and a sufficient coverage of data communication demands. A detailed analysis of the correlation between communications range, connectivity and available aircraft can be found in (65). As we later discuss in Section 7.5achieving a high communications range is not trivial and presents a significant challenge for the design of the A/A data link.

7.2.4 Aircraft Relative Speeds

A/A data links between aircraft have to be stable even if aircraft are moving at a high relative speeds. While focusing on commercial air transport, it seems reasonable to assume that the maximum relative speed occurs when two aircraft fly towards each other. As commercial airliners operate below the sound barrier, typically in the range of Mach 0.75 - 0.85, a value of Mach 2 can be assumed to represent a conservative requirement for the data link. However, if supersonic aircraft are intended to be included in the AANET, higher speeds might need to be considered.

7.2.5 Flight Altitude

Commercial airliners generally operate up to flight level FL600. Therefore, the data link should also be able to operate up to this altitude (67).

7.2.6 Cluster Formation

As the nodes in the AANET are spread over a considerable large geographical area and are highly mobile, clusters of interconnected aircraft are formed, that are not necessarily connected to each other. Even isolated clusters of interconnected aircraft occur having no connection to ground. An analysis of cluster formation for AANET on the NAT can be found in (69). It is shown that aircraft equipage fraction and radio communication range strongly influence cluster formation.

7.2.7 Gateways and Bottlenecks

Aircraft within the AANET with connectivity to ground stations might act as gateways to relay data between the ground and the AANET. These aircraft might see a considerably higher data rate as all the A/G data need to be routed through them. The availability of gateways also depends on the total available and equipped aircraft. As it is assumed that each aircraft might act as a gateway, the communication module is required to provide this functionality. An analysis of gateway availability can be found in (69).

In addition, not only the gateway aircraft might have to deal with higher data rates, but also aircraft affected by bottlenecks appearing in the AANET. This shall be considered in the design of the AANET.

7.2.8 Ground Stations

The placement and number of ground stations (GSs) is another aspect that strongly influences the performance of the AANET in terms of A/G communications. While (12) assumes only a very limited number of GSs to cover the North Atlantic, 47 GSs at the locations of present VHF ground stations from ARINC and SITA are assumed in (65) and (66). In any case, having more ground stations available at the edge of the ORP airspace yields a better A/G connectivity of the AANET.

7.3 Data Types

Depending on the application, different types of data need to be transferred by the data link. The following list gives a first overview of data types. Depending on the application, other types of data might need to be transmitted.

- Position
- Speed
- Wind
- Meteorological Data (maps)
- 4D Trajectories
- CPDLC data
- Text Messages
- Flight Plan
- Data stream (CVR, FDR)

7.4 Data Rates

We suggest to base data rate requirements for an AANET on today's established applications with A/G unicast communication schemes while taking into account future applications via appropriate multipliers.

7.4.1 Low Data Rate A/G Applications

Applications that are essential for the safe operation of flight (ATS, AOC) can be considered to require low data rates. The minimal required data rate for the AANET resulting from this can be assessed by applying the current usage of ATS and AOC applications in the respective ORP airspace. A representative data communication demand pattern has been presented in (70) and an assessment of resulting data rates within an AANET has been performed in (66). It was shown that, assuming a minimum radio range of 120 NMi for covering ATS and AOC applications in the North Atlantic ORP airspace alone, the A/A data link should be able to transmit with data rates of up to 2 kbps on average and 15 kbps peak. However, these data rates only address application data and do not take into account the overhead generated by network establishment and data routing. Furthermore, an ideal connectivity between all aircraft within radio range and equal distribution of data communication between all gateways of a cluster were assumed.

7.4.2 High Data Rate A/G Applications

Other applications with A/G unicast communication schemes, but significantly higher data rates, such as voice applications (average data rate of 4.9 kbps (25)) as well as aircraft passenger communication (data rates of up to 10 Mbps per passenger (26) or 100 Mbps per aircraft (71)) are not included in the aforementioned data rates. These applications would add a significant amount of data traffic within the whole AANET cluster leading to higher required data rates for both average as well as peak values.

7.4.3 Single Event A/G Applications

The impact of single event applications such as the OBB can be assessed by adding the single data rate of one application activation. In the case of OBB, one can expect data rates of up to 12 288 kbps for flight data recording and up to 256 kbps for voice recording (42). Assuming the worst case of only one gateway aircraft in a cluster and only one OBB activation at a time during a communication demand peak this would increase the peak data rate from 15 kbps to 283 288 kbps, if data are to be transmitted with minimal latency. In case increased latency and data buffering are acceptable for the OBB application, then the resulting peak data rate might be significantly lower.

7.4.4 A/A applications

Further applications that do not address A/G unicast communication such as pilot-to-pilot messages, event dissemination, addressed messaging or applications related to flight coordination between two or more aircraft (self-separation, relative positioning, loose formation flight, wake energy harvesting, air-to-air refuelling, aero-towing) would also add individual application related data rates to the aforementioned average and peak values, assuming that these applications rely on direct A/A connections. For indirect A/A connections, further assessments of data rate impact on the whole cluster formation have to be performed.

7.5 Technical Data Link Design Challenges

The design of the A/A data link presents numerous challenges, especially for the design of the physical and medium access control (MAC) layers, as discussed in (21).

7.5.1 Operational Challenges

Physically, the high altitude of the en-route aircraft leads to aircraft transmissions reaching far distances, as they are not impaired by the earth curvature until a long distance. For example, an aircraft flying at 18 km might receive transmissions from other high-altitude aircraft located almost 600 NMi away. In principle, this could be beneficial for some applications, as having a high communications range allows more aircraft to join the mesh network and to profit from the applications enabled by it. However, achieving a high communications range is not trivial for the data link, because it might require to either increase the radiated power, use more complex antenna configurations, or use more robust coding and modulation schemes, which might be only feasible up to a certain extend and can additionally decrease the overall data link performance. In addition, a high radio range leads to a composed background interference that affects the desired incoming signal and shall be taken into account in the physical layer design.

7.5.2 System Design

As shown in (10), the position and number of aircraft antennas are critical for the performance of an A/A data link, given that the aircraft fuselage blocks the signal transmitted to or received from certain directions, depending on the location of the antenna. In addition, some aircraft maneuvers might aggravate this effect, for example during take-off, landing, and banking maneuvers as observed in (24; 10). Given that A/A communications are also required during such maneuvers, they must also be taken into account in the physical layer design.

7.5.3 Physical Layer

The physical layer must also cope with the A/A channel, which might be challenging in some scenarios. For example, the high speed of the aircraft leads to a high Doppler frequency shift. Also, the A/A channels present a strong specular reflection component off the earth surface, which is specially strong over water as shown in (10). In addition to this component, the A/A channel presents scattering components whose strength, delay, and Doppler frequency shift distributions vary depending on the scenario (72) and might be non-negligible for low-flying aircraft (10).

7.5.4 MAC Layer

The design of the MAC layer is challenged by the fact that no central entity organizes the transmissions from the different aircraft, and they must find a way to organize their transmissions and/or to deal with the message collisions. The different MAC protocols provide a significantly different performance as shown for the AANET in (22). This is aggravated by the high aircraft mobility, which lead to changes in the network topology that must be taken into account not only by the MAC protocol but also by the routing protocol (73; 74).

Finally, the design of the A/A data link shall take into account that the aircraft distribution is radically different depending on the airspace. For example, a low number of sparse aircraft can be expected in ORP regions, whereas some continental regions present a heavily populated airspace (22). In addition, a high communications range might lead to long propagation guard bands to avoid messages collisions if time-division approaches are used, which reduces the throughput of the system.

7.5.5 L-Band Operation Conditions

In case the A/A data link operates in the aeronautical L-band, its design must also account for a series of additional challenges. First, many legacy systems operate throughout the L-band, leading to little spectrum available for a new system. Second, the available spectrum cannot be freely utilized, but it must be guaranteed that no system operating in the L-band is affected by the new A/A data link. For this, compatibility scenarios must be defined and the impact of the A/A data link on the other systems must be assessed, as done already for the new LDACS A/G system on other legacy systems (e.g. (75; 76; 77)).

In addition, compatibility criteria must be agreed upon with the corresponding authorities in order to derive under which conditions the new system can operate in the L-band. Finally, as the distance measuring equipment (DME) and the tactical air navigation system (TACAN) use different frequency channels depending on the location, some frequencies are only usable by the A/A data link locally and can only be found by following a careful frequency planning as the one proposed in (23), which must take into account the agreed compatibility criteria between systems. As part of the compatibility criteria, the A/A data link might see its maximum transmit power and duty cycle limited. Although these restrictions might also come from power-consumption budgets, the compatibility with the legacy systems generally tends to be more restrictive. This might lead to a lower communications range and a lower net data throughput.

In addition, frequency-dependent restrictions as the one presented by the International Telecommunication Union (ITU) in its resolution 417 (78), which limit the maximum transmit power of new systems in order to protect some of the legacy systems of the L-band, lead to some parts of the spectrum becoming effectively not utilizable by a new system.

8. Discussion and Outlook

In this paper, we presented applications for AANETs operating in the L-Band and identified challenges and requirements from the application, operational and technical perspective. Although the list is non exhaustive, it provides an overview of the possibilities enabled by such systems.

As many possible applications of AANET already exist today, one of the main advantages of such a system can be found in the redundancy it provides in case of outages of the legacy communication systems. Additionally, if the AANET provides ranging and positioning capabilities, it might provide an APNT solution in case of GNSS outage and, hence, ensure safe and efficient operation of aircraft in highly frequented ORP airspaces such as the North Atlantic.

As the AANET performance is strongly influenced by the available nodes and communication range, especially in the initial phase of its deployment, limitations will occur. However, once the AANET is operational, an additional set of new applications and procedures such as aircraft wake surfing, air-to-air refuelling or self separation can strongly benefit from it or even be enabled by it in the first place.

In this work, we also point out some of the main challenges in the design of the A/A data communications system that the AANET will be based upon.

The mobile ad-hoc nature of the network and the stringent performance requirements required for some safety of life applications lead to a very challenging MAC protocol design. This is additionally burdened by the required high communications range and high relative speed between the aircraft, which the physical layer must cope with.

Additionally, in order to operate in the aeronautical L-band, the A/A data link must be able to use the little vacant spectrum very efficiently and be robust against interferences while avoiding any harmful interference towards other systems

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Contact Author Email Address

tobias.marks@dlr.de

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