33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

ASSESSMENT OF REAL-TIME DATA TRANSMISSION VIA AD-HOC COMMUNICATION NETWORKS IN THE NORTH ATLANTIC OCEANIC AIRSPACE

A. Hillebrecht[1], T. Marks[1], V. Gollnick[2]

[1]German Aerospace Center, Air Transportation Systems, Blohmstr. 20, 21079 Hamburg, Germany
[2] Hamburg University of Technology, Institute of Air Transportation Systems, Blohmstr. 20, 21079 Hamburg, Germany

Abstract

Data link based real-time data transmission for air traffic services and aeronautical operational control provides for safe, efficient and timely exchange of information between aircraft and ground entities within the current air transportation system. This enables procedures and process optimization for air traffic service and airline operational control. Currently, the air transport system relies on direct line-of-sight data link in continental airspace and communication via satellite or high frequency data link in oceanic, remote or polar airspace. Future communication technology intends to additionally allow for indirect air-to-ground communication via aeronautical ad-hoc networks using aircraft as network nodes. This approach bears a high potential to increase airspace capacity and efficiency for congested airspaces with little ground infrastructure as it is the case e.g. for the North Atlantic oceanic airspace. While the assessment of operational benefits for conventional line-of-sight or satellite-based data link technologies can be based on the experience made with existing technologies, the assessment of aeronautical ad-hoc networks needs careful consideration of the particular air traffic situation as well as of the specific aeronautical communication demand. In our work we present a method to combine air traffic and connectivity simulations with an aeronautical data traffic demand model for the North Atlantic oceanic airspace. As a result, the coverage of aeronautical data traffic demand by an aeronautical ad-hoc network enabled by the new technology, will be estimated for various scenarios for the North Atlantic oceanic airspace. Dependencies on the equipage fraction and on the air-to-air radio range will be analyzed. Also, expected application data rates at aircraft exchanging the data communication of the airborne network with ground entities, will be assessed on a simplified basis. The results are suited to serve as a technical guidance for further scaling and definition of the underlying air-to-air data link technology.

Keywords: air transportation system, data link, communication, aeronautical data traffic

1. Introduction

Data link based real-time data transmission for air traffic services (ATS) and aeronautical operational control (AOC) are widely established within the current air transport system as a means of communication. Especially in airspaces with high traffic density, data communication increases airspace capacity limited by conventional voice communication technology and has the potential to enhance safety and efficiency for air traffic management and airline operations management. Furthermore, a higher bandwidth of the data link systems can enable new air traffic services and procedures. With regard to AOC, data communication is a basis for the transmission of in-flight information to the airline operational control center, enabling optimization of aircraft operation.

Consequently, aeronautical data link communication plays a central role in the plans of e.g. ICAO and SESAR for the evolution of flight guidance avionics [1, 2]. Currently only ground based line-of-sight or costly satellite-based technologies are available, which in case of oceanic, remote or polar (ORP) airspaces often is limited to the latter without an alternative fallback option. Also, the so-called L-Band Digital Aeronautical Communications System (LDACS) [3], set to be the new candidate for future continental data link technology [2], enables connectivity between aircraft and ground entities and is, therefore, initially intended for continental airspaces only.

Using the LDACS technology to build up direct air-to-air (A2A) data link capability, however, would not only enable direct information exchange between aircraft but also the forwarding of messages to ground entities using aeronautical ad-hoc networks. This capability is currently being assessed in the project IntAirNet funded by the German Ministry of Federal Ministry for Economic Affairs and Climate Action (BMWK). This provides a feasible, potentially more cost-efficient, alternative technology for aeronautical data communications in airspaces with high traffic load but without the option to use ground-based communication technology, such as the North Atlantic oceanic airspace (NAT).

Apart from possible cost benefits, which might not be a prime driver in face of decreasing cost for satellite links, an aeronautical ad-hoc network can supply aircraft with a fallback option for data communication in ORP airspaces. Hence, an increasing transmission stability and data link availability can be expected enhancing the overall communication system performance in combination with satellite systems. Aeronautical ad-hoc networks enabled by direct air-to-air datalink can, therefore, pose a significant supplement to existing communication performance via satellite and might pave the way for more efficient flight operations in ORP airspaces.

Whether data communication via an aeronautical ad-hoc network is a suitable option for setting up a viable alternative communication channel in ORP airspace, is highly dependent on the operational value that it provides. Other than conventional air-to-ground (A2G) or satellite data links, the performance of an aeronautical ad-hoc network using A2A data links is mainly influenced by the presence of other aircraft and the overall air traffic situation. Only with a sufficient number of aircraft equipped with the necessary systems in a suitable geographical distribution within the airspace, a connection to a ground station can be established.

The communication range and the equipage fraction, accordingly, are crucial parameters that have to be analyzed in combination with the aeronautical communication demand of each aircraft connected in such an aircraft network. Additionally, the formation of clusters in the particular airspace environment and the accumulation of data traffic on single aircraft acting as gateways or bottlenecks need to be addressed. These effects potentially limit the applicability of aeronautical ad-hoc networks to particular airspaces and timeframes and requires careful consideration.

2. Related Works

A number of previous studies have addressed the usage of aeronautical ad-hoc networks in oceanic airspace [4–6], which usually focus on the design of effective network routing protocols, and the resulting capacity to transmit data within the aeronautical ad-hoc network. Other studies have developed aeronautical data communication demand (ADCD) for air traffic services and airline operational control, with a focus on continental airspace [7–9]. Also, a series of projects in the context of the Single European Sky efforts have assessed capacity and performance of existing and planned communication infrastructure in continental airspace [10, 11].

In [12], Vieira et al. establishes an analytical network coverage description for mobile ad-hoc networks with the number of network nodes and the communication range as relevant parameters. In our work, we follow an empirical approach to assess the coverage of ADCD and expected transmission requirements by simulating air traffic and the data communication of every single airspace user, which is then used for a parametrized connectivity assessment. As a relevant scenario the NAT has been chosen, which has been identified by several previous studies as a suitable application scenario for aeronautical ad-hoc networks [4–6].

With regard to air traffic and connectivity modelling, our work is relying on two previous studies, where an approach for has been introduced and ADCD models for AOC and ATS applications tailored to the NAT have been derived and implemented [13, 14]. Both serve as a basis for the ADCD coverage description and assessment of transmission requirements presented in this work.

2.1 Air Traffic and Connectivity

In Marks et al. (2022) [13] aircraft connectivity in the NAT airspace has been assessed using flight plan data from October 2019 and assuming geodetic flight paths between airports. The data was filtered to those flights, that cross the respective airspace and split into east- and westbound traffic datasets in order to take the separation of east- and westbound traffic routes due to the North Atlantic organized track system (OTS) into account.

The assessment of Marks et al. (2022) [13] defines key metrics describing core properties of the aeronautical ad-hoc network and the resulting connectivity. Among those key metrics are the air-to-air connectivity, air-to-ground connectivity, link duration and available number of connections, which vary depending on the assumed communication range and fraction of aircraft, that are equipped with the required communication technology.

Furthermore, Marks et al. (2022) [13] conclude, that both equipage fraction and A2A communication range both have a strong influence on the aforementioned connectivity metrics. They present their method to be a suitable approach for identifying the required A2A communication range and equipage fraction in order to achieve a desired level of connectivity.

2.2 Aeronautical Data Traffic

The demand for ATS and AOC aeronautical data communication in the NAT has been assessed by Hillebrecht et al. (2022) [14]. With regard to ATS, their work establishes a model for data communication based on operational constraints imposed by air traffic management procedures, technical standards and data communication performance monitoring reports for the NAT. The presented AOC data communication model relies on a comprehensive assessment of ADCD by EUROCONTROL and NASA [8]. The differentiation between ATS and AOC aeronautical data communication is not only motivated by the different sources of information used for assessment and modelling but also by different requirements to communication performance. While ATS data communication has to follow a defined set of performance requirements prescribed by the respective regulatory authorities [15–17], AOC data communication is of lower criticality.

In their work Hillebrecht et al. (2022) [14] derive a set of data link-based communication services under consideration of specific requirements arising from OTS usage and hand overs. The model is then applied to the air traffic mobility and connectivity data as created in [13] yielding an overall communication demand for the NAT in the simulation time slot. With regard to ATS data communication average numbers of incoming and outgoing messages per aircraft and per oceanic control area (OCA) are then assessed and validated against performance monitoring data provided by ICAO.

In a further analysis it is shown, that the AOC domain in terms of data volume is dominated by a single data intensive service describing the transmission of visual weather information to an aircraft (94% of total AOC data volume), which only makes up for a small portion of messages in the AOC domain (12% of all AOC messages). For the ATS domain messages that are small in data volume (i.e. size of 34 bytes) prevail and make up 97% of the total amount of messages generated and 80% of the total ATS-related ADCD.

Also, Hillebrecht et al. (2022) [14] show how the communication demand of single ATS and AOC services is geographically distributed within the simulated portion of the NAT. Notably along borders of control areas, along waypoints and fixed reporting intervals, airspace dependent distribution patterns occur and cause a non-homogeneous distribution of communication demand.

3. Methodology

In our approach we perform an operational assessment of ad-hoc network-based aeronautical data transmission and the underlying technology, which is applied to a scenario of ATS and AOC data communication in the NAT oceanic airspace. In order to simulate effects of the OTS, which is in place in this airspace, east- and westbound traffic flows will be analyzed separately, with the results for westbound traffic presented in this work. The analysis will rely on connectivity modelling using flight plan data from 2019 as presented in [13]. Aeronautical communication patterns for the NAT oceanic airspace [14] will then be applied to the simulated air traffic allowing for the identification of coverage of the ADCD and initial evaluation of demand-inflicted application data rates. The latter requires an assessment of data demand occurring within clusters, formed by connected aircraft. Apart from the allocation of each aircraft to a particular cluster, this also requires the identification of aircraft serving as gateways and providing a connection between airborne cluster and ground communication infrastructure. Both is provided as connectivity data by [13]. As the focus of the study is on operational usability and functional assessment, only data on application level will be considered. Data overhead as typically caused by data routing in a network is not included.

As a result, we will show, which share of messages and data volume can be transmitted via an aeronautical ad-hoc network in the considered scenario, depending on data link range and equipage fraction.

Figure 1 shows the general approach that is followed in this work to achieve an operational assessment of expected maximum data rates for interconnected airborne clusters and gateway aircraft as well as the potential ADCD coverage of the aeronautical ad-hoc network. The connectivity simulator is summarized in section 2.1 and described in detail in [13]. The data traffic generator and related input and output data is summarized in section 2.2 and described comprehensively in [14]. The connectivity data and the data traffic demand that are resulting from simulations with connectivity simulator and data traffic generator respectively are then fed into the cluster data rate assessment, which will be further described in the following sections.

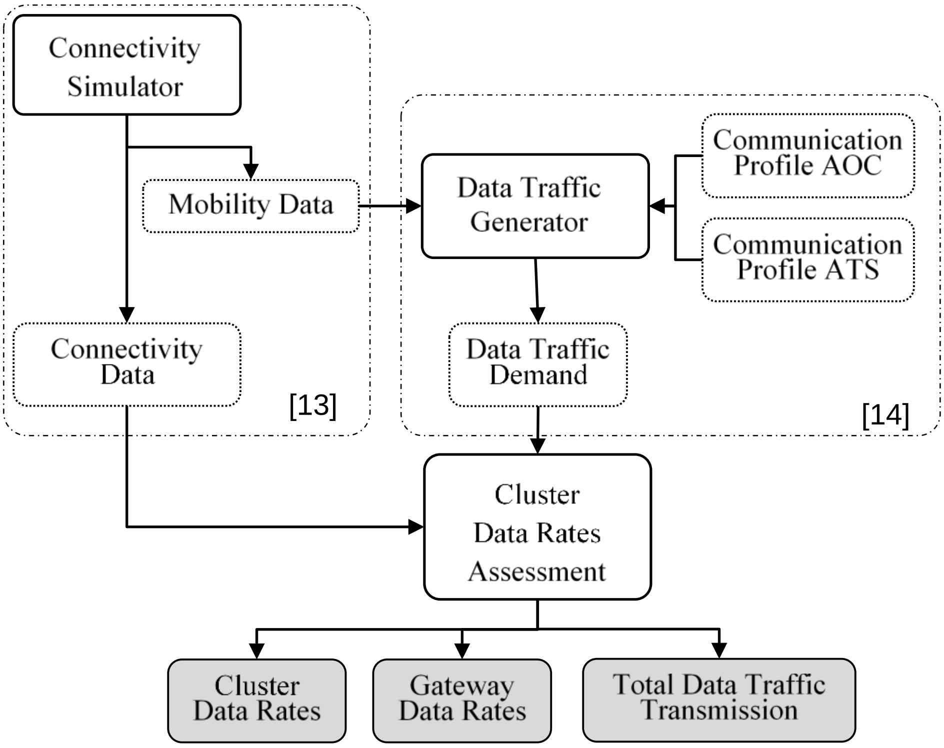

Figure 1 – General approach as followed within this work

3.1 Definitions

In this section basic definitions will be presented, which will be used in the description of methodology, results and discussion of results.

3.1.1 Air-to-Air (A2A) Connection

In the context of this work an A2A data link connection is defined to be the direct connection between two aircraft, of which at least one aircraft is within the applicable simulation area (ASA), which is described in section 3.2.1.

3.1.2 Air-to-Ground (A2G) Connection

An A2G connection is defined as the connection between an aircraft and a ground station.

3.1.3 Cluster

Generally, a cluster is formed by at least two aircraft connected via A2A connection. In the context of this study, we define a cluster as a group of aircraft that are connected via A2A connections with at least one aircraft having an A2G connection to a ground station in range. Aircraft without connectivity to other aircraft and interconnected groups of aircraft without ground connection are not considered.

3.1.4 Gateways

A gateway is defined as an aircraft that has both A2G connection with at least one ground station as well as an A2A connection with other aircraft in the ASA that does not have an A2G connection itself. Thus, a gateway aircraft is feeding the data traffic from the aeronautical ad-hoc network to a ground-based network, which will then distribute the data traffic to air traffic control centers or airline operational centers.

3.1.5 Aircraft Sets

The set of all aircrafts contained in a scenario at a time step t is given by $S(t)$. Subsets of S are used to describe sets of aircraft that share a common property. One relevant subset is the set of all aircraft that is part of an interconnected cluster j at timestamp t. This set is described by $S_{CL}(j,t)$.

Another relevant subset of aircraft is the set of all aircraft within a cluster j at a timestamp t, that serve as a gateway to a ground station. This set of gateway aircraft is described by $S_{GW}(j,t)$.

3.1.6 Scenario Parameters

Aircraft connectivity in a scenario is varied over two parameters – equipage fraction e_f and A2A communication range r_a – as described in Marks et al. (2022) [13]. Equipage fraction defines the fraction of aircraft within an air traffic scenario, that is equipped with the required hardware for establishment of direct A2A links between aircraft. A2A communication range, r_a, is the maximum range up to which such a data link connection can be established.

3.1.7 Connectivity and Communication Parameters

The communication demand is driven by the set of implemented ATS and AOC services which are triggered by operational conditions linked to the airplanes flight path, on a randomized basis or based on time thresholds. The set of underlying ATS and AOC services is described in detail in Hillebrecht et al. (2022) [14]. Each service is comprised of several single messages, which are labelled communication event (ε). The amount of data resulting from all communication events in a defined part of the airborne network in a defined timeframe is the resulting data rate (δ). Data traffic resulting from ATS or AOC services is labelled accordingly δ^{ATS} or δ^{AOC}.

Communication events can be transmitted in forward direction from an originating aircraft to a receiving ground entity or aircraft and in reverse direction from an originating ground entity to a receiving aircraft. Resulting data traffic is labelled forward link (FL) or reverse link (RL) respectively.

3.2 Scenario Setup

The scenario is defined by geographical area, air traffic, communication demand of each aircraft and connectivity between aircraft.

3.2.1 Applicable Simulation Area

As described in [13] and [14] the North Atlantic oceanic airspace with a focus on the airspace relevant for the North Atlantic organized track system has been identified as a suitable scenario for the operational assessment of A2A datalinks and aeronautical ad-hoc networks. The applicable simulation area (ASA) is comprised of the NAT oceanic control areas, which are

- Reykjavik Oceanic (BIRD),
- Bodo Oceanic (ENOB),
- Gander Oceanic (CZQX),
- Shanwick Oceanic (EGGX),
- New York Oceanic (East) (KZWY) and
- Santa Maria Oceanic (LPPO).

Only the area North of 39th parallel is considered, excluding parts of KZWY and LPPO oceanic control areas. Outside of the ASA, but still considered for the simulation of air traffic are boundary zones to the east and west with a buffer range of 420km. Air traffic within the boundary zones is only included in connectivity and data traffic considerations, if it serves as communication gateway for network clusters within the ASA.

3.2.2 Air Traffic

In this work we consider an air traffic data set with westbound flights only, which has been generated as described in section 2.1 with the approach by Marks et al. (2022) [13] The total set consists of 665 flights.

3.2.3 Connectivity

With regard to connectivity of aircraft and ground entities two types of connections and their respective communication ranges are relevant. One is the A2G range, r_g, and the other one the A2A range, r_a. As described in [13], r_g is set to a fixed value of 370 km, while for r_a a sequential variation from 0 km to 420 km with steps of 15 km is applied.

The other parameter being varied in the connectivity analysis, the equipage fraction e_f, follows a sequential variation from 0% to 100% with steps of 10%. For each value of e_f, 10 samples of equipped aircraft are selected. For $e_f = 1$ only one sample, that includes all aircraft is used. The total number of simulated scenarios within the connectivity assessment is 2,900. The scope of variations is shown in Table 1.

Table 1 – Parameter variations

symbol	variation	unit
e_f	0 : 0.1 : 1	-
r_g	370	km
r_a	0 : 15 : 420	km

The affiliation to interconnected clusters, as well as A2A and A2G connections are then identified for every time step and each aircraft for all simulated scenarios.

3.2.4 Aeronautical Data Communication

We use the aeronautical data communication model developed by Hillebrecht et al. (2022) [14] as described in section 2.2. With this approach the highest congruence with recorded ATS data communication behavior is achieved in the central OCAs of Gander (CZQX) and Shanwick (EEGX), which also account for the highest air traffic load in the scenario of regard.

ATS data communication is predominantly characterized by service activations along airspace borders, pre-defined waypoints, reporting intervals with only a few services being dependent on flightpath-related events instead, causing more evenly distributed geographical demand pattern. AOC data communication on the other hand is independent from the structure of OCAs and considers a series of services with randomized or fixed activation intervals.

Due to the stochastic nature of several services, which are mainly part of the AOC domain, a total of 10 data traffic demand variations are generated.

3.3 Coverage and Data Rate Assessment

Based on the connectivity between air traffic participants in the selected scenarios and their aeronautical data communication, we assess which fraction of the total ADCD can be transmitted using the aeronautical ad-hoc network. This is achieved by combining every scenario described in section 3.2.3 with every data traffic variation, as presented in section 3.2.4, yielding a total of 29,000 settings.

In this context it will be assumed that any data communication can be transmitted, that is occurring while the receiving or emitting air traffic participant is part of a cluster with ground connection, neglecting possible network data overhead, transaction delays and using fixed intervals between messages as presented in section 3.3.1.

3.3.1 Message Intervals

The aeronautical data traffic model as described in section 2.2 contains a series of service activation times for all ATS and AOC service activations of all flights within the ASA and the simulation timeframe. The service activations as described in the aeronautical data traffic model contain a series of single RL and FL messages, which are in detail described in [14]. Based on this definition, service activations as resulting from the aeronautical data traffic model are decomposed into the single messages and a fixed time interval between two message timestamps of $d_t = 0.1\ s$ is assumed. An exemplary message sequence of the clearance request and delivery service, which is part of the ATS service set is shown in Figure 2.

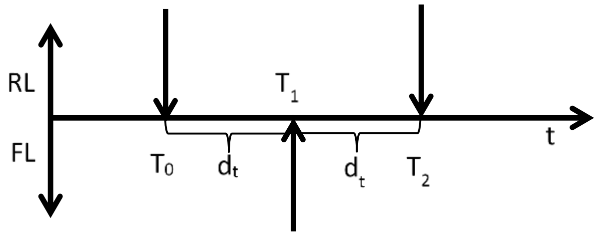

Figure 2 – Message spacing of clearance request and delivery service

Accordingly, all messages have the same time spacing to previous and following messages of the same service. This simplification of data transaction times and spacing between messages of a service enables a data rate assessment based on operational communication demand and air traffic occurrence. Once detailed parameterized network and data link models are available, a refined model for d_t with dependencies on communication range, network topology and message size can be used.

3.3.2 Time Continuous Clusters

As described in section 3.2.3, clusters are identified individually per timestamp within the connectivity assessment of [13]. In order to allow for consideration of transmission delays, during which cluster allegiance and transmitting gateway aircraft might change, allocation of time-continuous cluster IDs is required. The cluster IDs of two different time steps are considered to belong to the same ad-hoc network cluster, if the majority of gateway aircraft is identical. Clusters that are newly formed or break away from an existing cluster receive a new cluster ID. Clusters without gateways are not considered for further assessment since no A2G transmission of data can take place.

3.3.3 Data Transmission per Aircraft

The amount of data sent or received (FL, RL) as part of the ATS or AOC service group by an aircraft within a time step is defined by $\varepsilon(t)$. The corresponding data rate then results to $\delta = \varepsilon/\Delta t$. Δt corresponds to the sampling time, which is 60 s for all results presented in this work.

$$\delta_{AC,i}^{Type}(t) = \sum_{t-\frac{\Delta t}{2}}^{t+\frac{\Delta t}{2}} \varepsilon_{AC,i}^{Type}(t) \cdot \frac{1}{\Delta t} \tag{1}$$

There are four different data transmission rates in order to describe data transmission caused by ATS or AOC applications in FL and RL respectively. The total data rate for a specific aircraft i at a time step t is described by the sum of these four data transmission rates.

$$\delta_{AC,i}^{all}(t) = \delta_{AC,i}^{ATS,FL}(t) + \delta_{AC,i}^{ATS,RL}(t) + \delta_{AC,i}^{AOC,FL}(t) + \delta_{AC,i}^{AOC,RL}(t) \tag{2}$$

In the further context of this study, we consider only the combined data rate of RL and FL data transmissions of both ATS and AOC services.

3.3.4 Data Transmission per Cluster

The data transmission rate per cluster for a specific cluster j is described by the sum of all data transmission rates of aircraft that are part of this cluster at the defined time step. The set of all aircraft i, that are part of cluster j at time step t are given by $S_{CL}(j,t)$.

$$\delta_{CL,j}(t) = \sum_{i} \delta_{AC,i}(t)\,, \forall\, i \in S_{CL}(j,t) \tag{3}$$

3.3.5 Data Transmission per Gateway Aircraft

The data transmission rate specific for a particular gateway aircraft k is defined by the cluster specific data transmission rate divided by the number of gateways $n_{GW,j}(t)$ in that cluster at the time step of regard. The set of gateway aircraft that are part of a cluster j at a time step t is described by $S_{GW}(j,t)$.

$$\delta_{GW,k}(t) = \frac{\delta_{CL,j}(t)}{n_{GW,j}(t)}, k \in S_{GW}(j,t) \tag{4}$$

It has to be noticed, that with the above definition only data transmission is considered, when a cluster j is connected to ground by at least one gateway. Also, data transmission is assumed to be equally distributed over all gateway aircraft of a cluster, yielding identical data transmission rates.

3.3.6 Total Communication Demand

The total communication demand C is described by the sum of all equipped aircraft related ADCD, that do not have a direct A2G connection and are within the ASA with $S_{A2G}(t)$ being the set of all aircraft being connected to a ground station at time step t.

$$C = \sum_{i} \sum_{t} \varepsilon_{AC,i}(t)\,, i \notin S_{A2G}(t) \tag{5}$$

The magnitude of total communication demand is influenced by both, the amount of equipped aircraft in the ASA as well as by the individual communication demand pattern of each aircraft.

3.3.7 Coverage of Communication Demand

The communication demand T, that is transmittable via the aeronautical ad-hoc network, is described by the sum of cluster data transmission rates added up over the simulation timeframe for all clusters but excluding the communication demand of gateway aircraft, since their communication demand is covered by a direct A2G connection.

$$T = \sum_{j} \sum_{t} \delta_{CL,j}(t) \cdot \Delta t - \sum_{j} \sum_{t} \varepsilon_{AC,i}(t)\,,\ i \in S_{GW}(j,t) \tag{6}$$

Set into relation with the total communication demand, the transmittable communication demand yields the communication demand coverage.

$$F = \frac{T}{C} \tag{7}$$

It has to be noticed that this metric only describes the fraction of ADCD that is transmittable under idealized data link assumptions neglecting effects of networking logics and physical data link limitations with regard to e.g. latency and bandwidth.

4. Results

Applying the methods described in section 3, we present the results with regard to transmittable fraction of ADCD (F), operational data rates at gateways with regard to mean and 99th percentile values ($\overline{\delta}_{GW}$, $\delta_{0.99,GW}$) as well as selected timelines for aeronautical data traffic generation within a cluster.

4.1 Cluster Specific Data Transmission

The basis for the calculation of δ_{GW} is the calculation of δ_{CL}. In this section δ_{CL}-timelines for those clusters with the longest cluster duration for three exemplary scenario settings as listed in Table 2 are presented. These are representative for a setup with high e_f and r_a (setting A), high e_f and low r_a (setting B) and low e_f and high r_a (setting C).

Table 2 – Settings for example scenarios

parameter	setting A	setting B	setting C
$\boldsymbol{e_f}$	0.8	0.8	0.4
$\boldsymbol{r_a}$	330 km	150 km	330 km

Figure 3 shows the δ_{CL}-timeline for the cluster with the longest cluster duration in setting A with the cluster duration time indicated on the x-axis, which represents a scenario with both high e_f and high r_a, resulting in a setting with high connectivity. This is characterized by high numbers of gateways and transmitting aircraft within the cluster, with maximum values of over 50 and over 200 aircraft respectively, and long cluster durations of up to 700 minutes. δ_{CL} reaches peak values of above 200,000 bps, but might surpass this value in clusters where less gateways per transmitting aircraft are available.

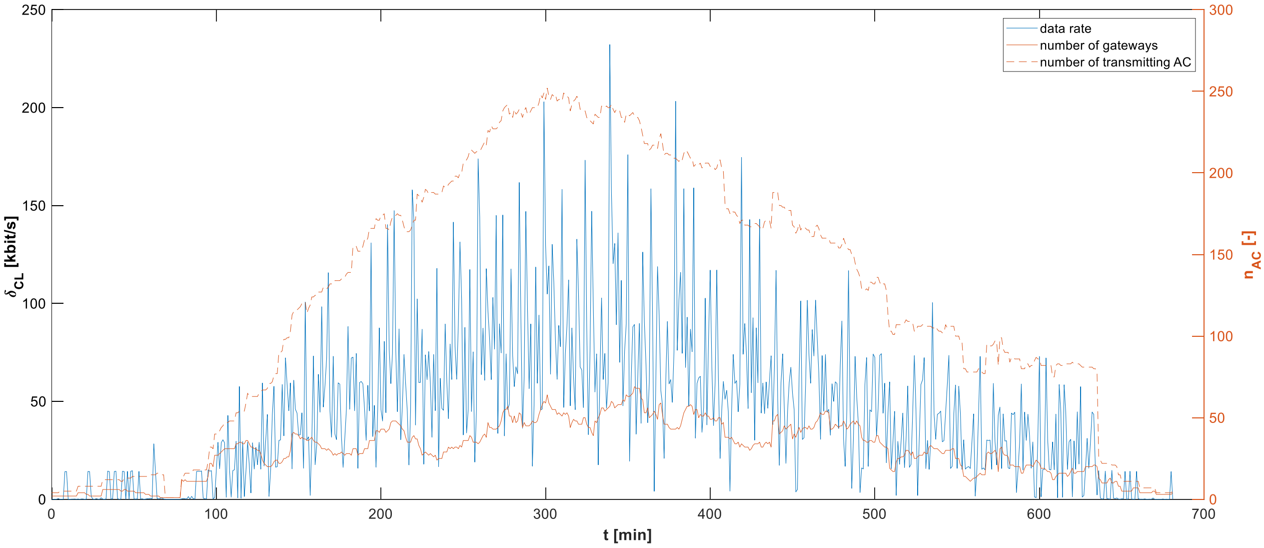

Figure 3 – δ_{CL} plot over time for setting A

The δ_{CL} for the cluster with the longest cluster duration in setting B is shown in Figure 4. Due to the different settings this does not necessarily correspond with the time plot shown in Figure 3. Here a significant reduction in connectivity due to a reduced r_a is observed, while the set of equipped aircraft remains the same. This yields in a reduction of transmitting aircraft within the cluster, not surpassing a maximum of less than 120 aircraft and a reduced number of gateway aircraft, which remain less than 10 for the most of the timespan. δ_{CL} is accordingly lower with maximum values of around 70,000 bps to 80,000 bps. Also visible is the cluster breakups after 140 minutes, when the remaining gateway aircraft loses connection with the ground network.

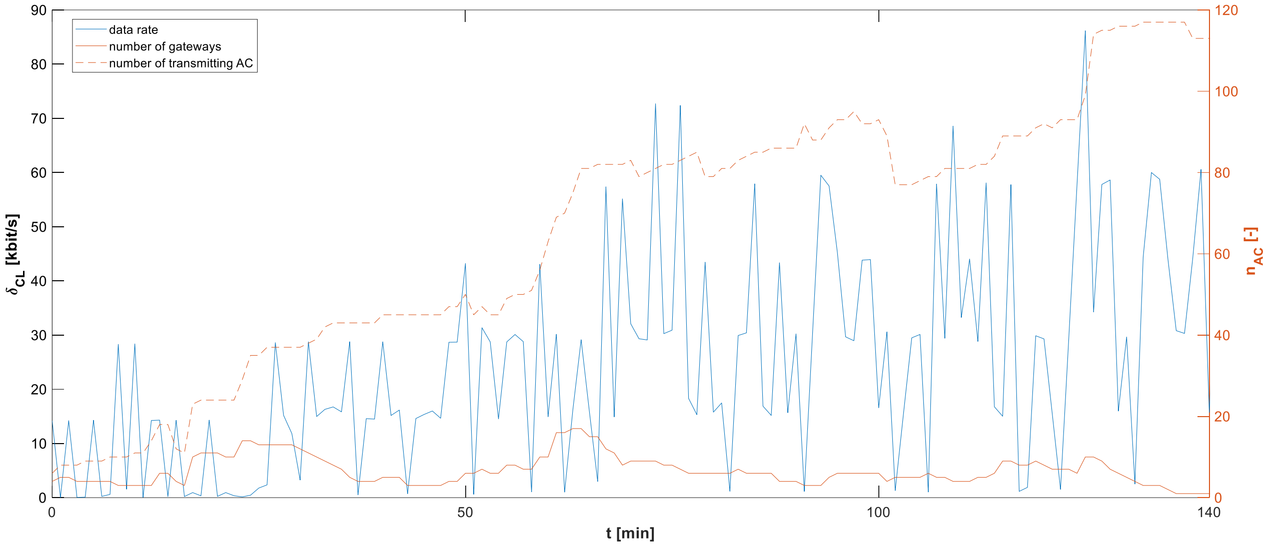

Figure 4 – δ_{CL} plot over time for setting B

Finally, the δ_{CL} timeline for the cluster with the longest cluster duration under setting C is shown in Figure 5. Again, the presented cluster does not necessarily correspond to those shown for settings A or B. It can be seen, that the cluster size, both in terms of transmitting and in terms of gateway aircraft, with around 120 and 20 aircraft respectively, is in between settings A and B. The same applies for δ_{CL} with maximum values of up to 110,000 bps and the cluster duration of around 500 minutes.

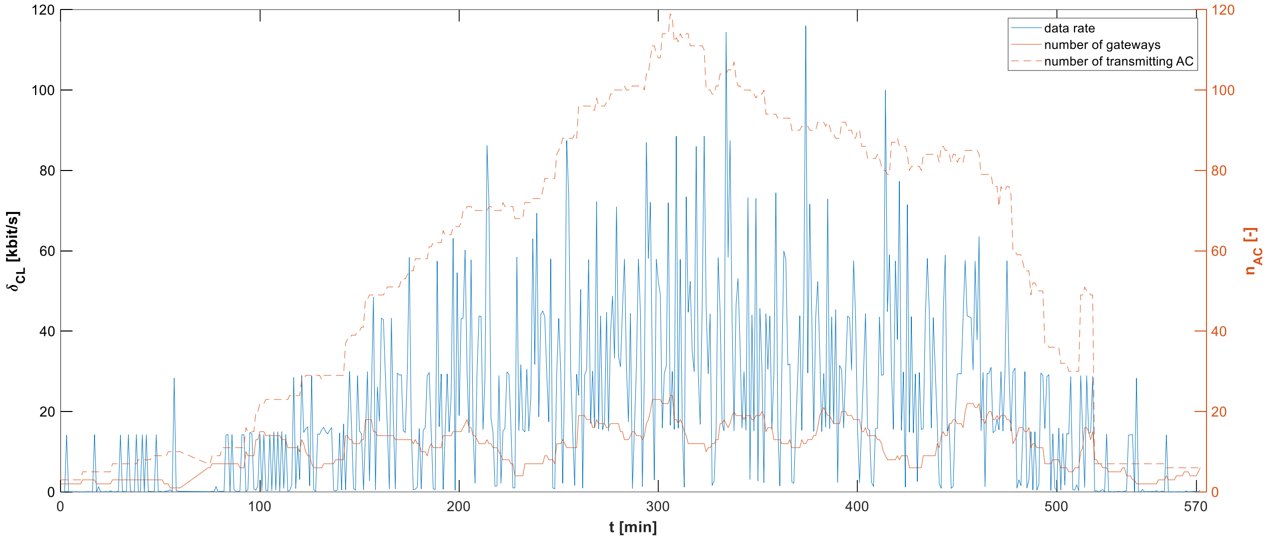

Figure 5 – Cluster data rate (δ_{CL}) plot over time for setting C

In summary, the presented δ_{CL} timelines for settings A to C indicate a higher impact of r_a in the range from 150 km to 330 km than e_f in the range from 0.40 to 0.80.

4.1 Overall Data Transmission Rates

Figure 6 shows the mean data rate at gateway aircraft, $\bar{\delta}_{GW}$, which peaks for r_a from 135 km to 165 km with e_f of more than 0.8 and reaches values of more than 2,300 bps. From values for r_a of above 165 km, the maximum values $\bar{\delta}_{GW}$ are lower with increasing r_a and e_f, even though as presented in section 4.2, a higher amount of data traffic demand is being transmitted via the aeronautical ad-hoc network. This might be linked to saturation effects, occurring if several smaller clusters merge into one bigger cluster, making more gateway aircraft available. In scenarios with low r_a and e_f, particular samples of e_f appear to cause small cluster setups that generate high values for δ_{GW}, while in general only few data points for δ_{GW} are established. Such is the case for the global maximum of $\bar{\delta}_{GW}$ at $r_a = 30\ km$, $e_f = 0.20$, due to a favorable recombination of equipped aircraft, in a setting which yields less data sample points.

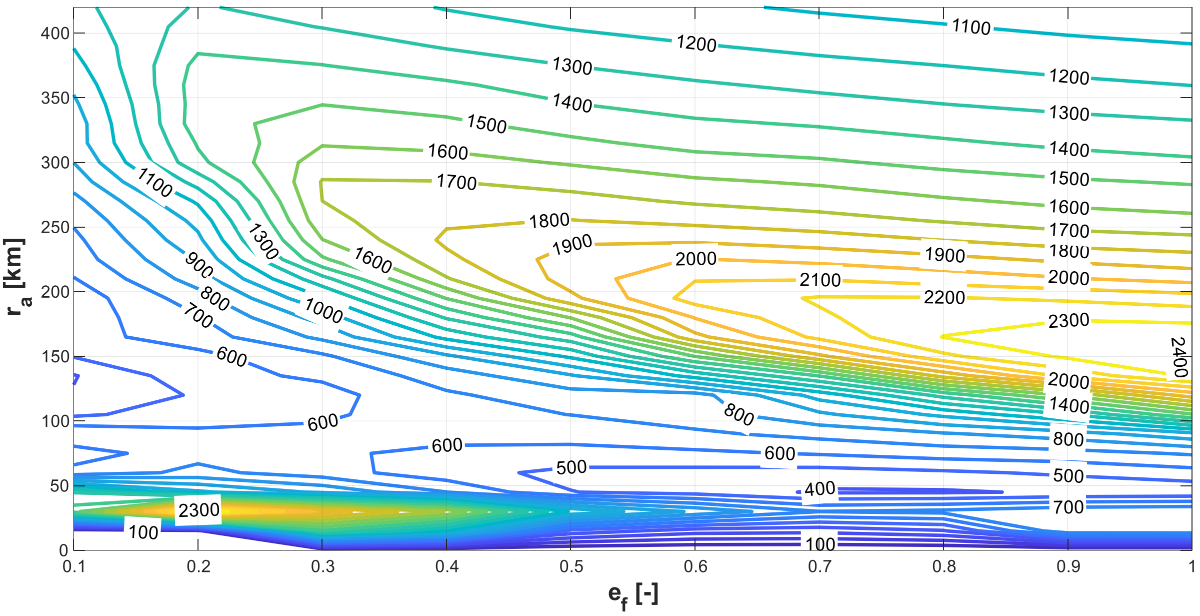

Figure 6 – Mean gateway data rate $[bit/s]$ ($\bar{\delta}_{GW}$) over equipage fraction (e_f) and A2A range (r_a)

The findings for the resulting δ_{GW} are also supported by the contour plot of the 99th-percentile gateway data rate ($\delta_{0.99,GW}$) in Figure 7. Values for $\delta_{0.99,GW}$ reach 24,000 bps at e_f of 1.0 with r_a between 100 km and 150 km and then remain constant up to r_a of 200 km. Then, $\delta_{0.99,GW}$ decreases with higher values for r_a and reaches values as low as 3,000 bps for r_a of 420 km and e_f of 1.0. e_f seems to have a lower influence on $\delta_{0.99,GW}$ in general with $\delta_{0.99,GW}$ slightly decreasing with increasing e_f.

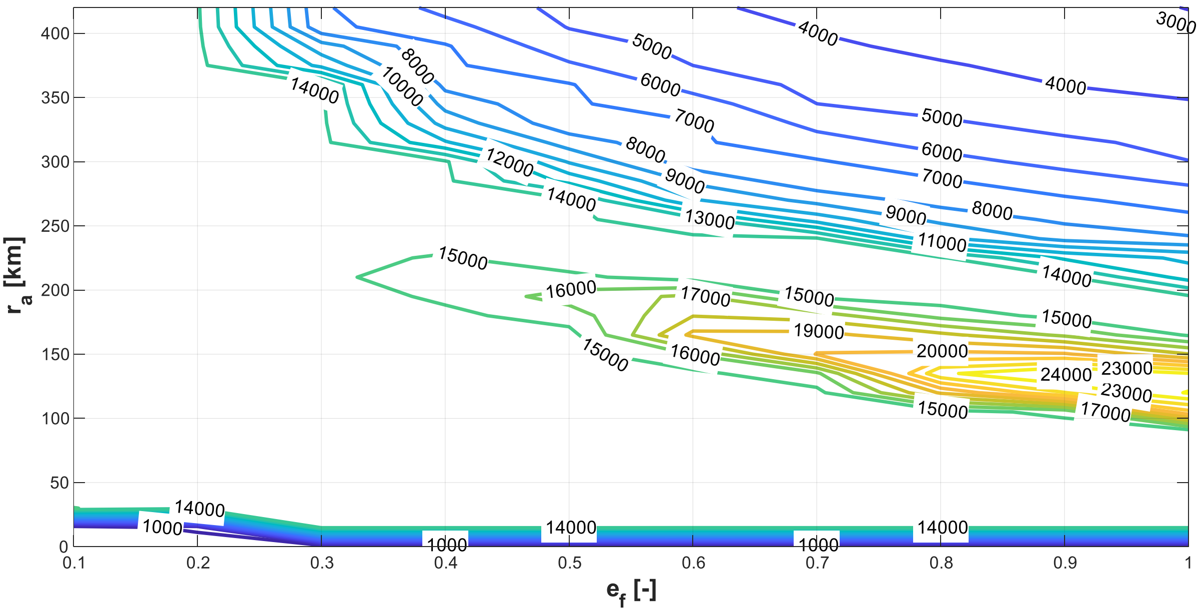

Figure 7 – 99th-percentile gateway data rate $[bit/s]$ ($\delta_{0.99,GW}$) over equipage fraction (e_f) and A2A range (r_a)

4.2 Coverage of Data Communication Demand

The dynamic coverage of aeronautical data traffic demand of equipped aircraft, as described by the fraction of data traffic demand, that is within the temporal and spatial coverage of the dynamic aeronautical ad-hoc network is shown in Figure 8. It can be seen, that with a maximum r_a of 420 km and e_f of more than 0.7 more than a fraction of 0.85 of the total aeronautical data traffic demand of equipped aircraft can be transmitted via the aeronautical ad-hoc network, assuming ideal conditions for data transmission within the network. Furthermore, a saturation of transmittable data traffic demand can be seen with r_a of 350 km and e_f of more than 0.5, where no significant increase of transmittable data traffic demand is observed. Also, with r_a below 100 km only a limited coverage of aeronautical data traffic demand of between 0.025 and 0.10 can be achieved in combination with e_f of at least 0.5, which hardly improves with higher values for e_f.

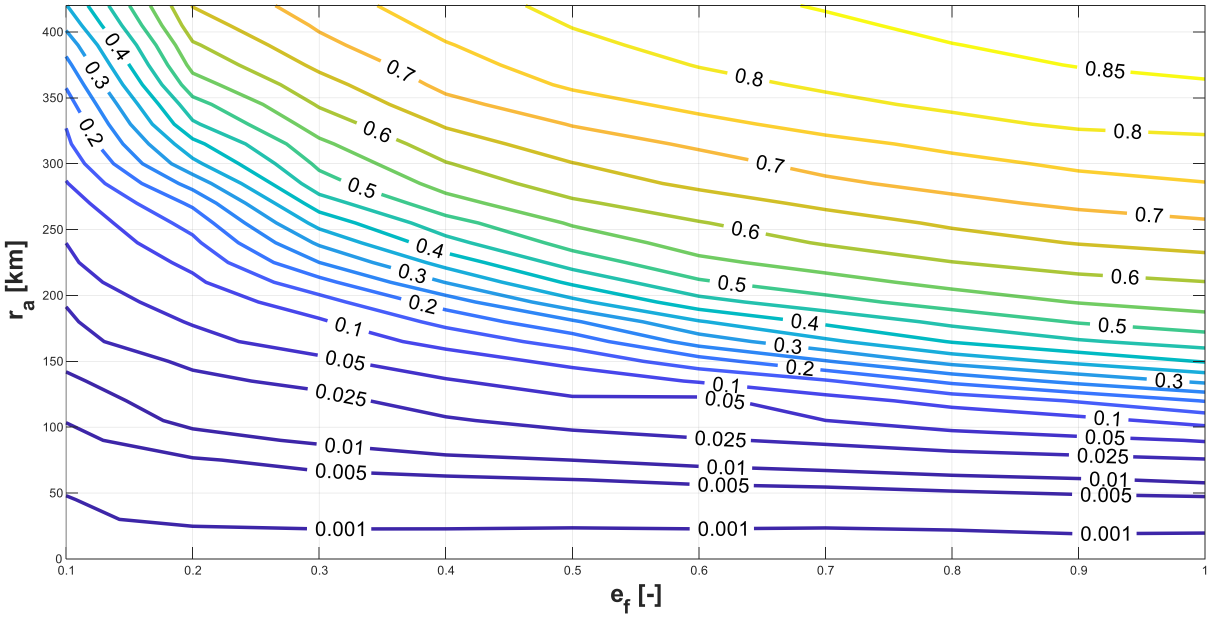

Figure 8 – Mean fraction of transmitted ATS and AOC data volume [-] ($\overline{F}$)

With regard to the gradient of transmittable data traffic demand in the direction of e_f, it has to be noted that the total volume of transmitted aeronautical data traffic is still increasing, since the transmitted data traffic volume is only weighed against the total data traffic demand of equipped aircraft within oceanic airspace. Even if only a fraction of 0.1 of all aircraft are equipped, these would still be able to transmit fractions of around 0.35 of their data traffic demand via the aeronautical ad-hoc network with an r_a of 420 km. It has to be noted that these values are based on the mobility data of 2019. For the assumption of a long-term reduction of air traffic in the North Atlantic (e.g. due to a permanent change of air mobility demand or limitation due to environmental considerations), the results could also be applied, provided that flight routes and timely spacing are similar in general. In this case the equipage fractions needed to achieve the above-mentioned coverages of data traffic demand would have to be increased accordingly. E.g. an equipage fraction of 0.8 in the scenario presented in this work would be equivalent to an equipage fraction of 1.0 in a scenario with 20 % less air traffic.

5. Discussion and Outlook

The results underline the high potential of aeronautical ad-hoc networks for the transmission of aeronautical data communication, as it has been found in an exemplary scenario that a fraction of more than 85 % of the occurring data traffic could be transmitted by equipped airspace users. Furthermore, the results offer a reference point for the development and scaling of the required transmission technology, which enables the A2A data link connection between aircraft. They also indicate, that such a technology should be capable of enabling transmission rates for application data of at least 1,800 bps on average and up to 15,000 bps for ADCD peaks. The results suggest, that the technology should be able to provide A2A ranges of more than 250 km to avoid local data rate peaks at lower equipage fractions, which would allow for between 65 % and 70 % of the equipped aircraft's ATS and AOC data communication to be transmitted via the aeronautical ad-hoc network, depending on the overall equipage of aircraft with the A2A data link technology. A higher A2A range would enhance the coverage for lower equipage fractions, such as they might occur during the ramp-up phase of the new technology while a further increase of A2A ranges up to the highest investigated value of 420 km would yield more than 85 % of transmittable ADCD.

Further considerations, which might shift these design parameters towards lower or higher values are of operational and economic nature, that apply to ATS and AOC communication in different ways, and should take the capabilities of alternative technologies for aeronautical data link communication such as satellite communication into account. Considering the performance requirements for ATS-related data communication, aspects such as communication availability and continuity as well as transmission delays are of primary concern. This might encourage an integrated solution of aeronautical ad-hoc networks with satellite communication, improving the overall system performance. The result might be higher A2A ranges with lower data rate limits, that are tailored to the less data-intensive ATS services (as it has been found in previous works). If economic and cost aspects prevail, such as it is the case with AOC-related data communication, lower A2A ranges in combination with support of higher transmission rates, might be favorable in order to supplement satellite communication with its higher cost and consistent coverage in ORP areas. In such a setup AOC services that are less time-critical but data-intensive, might pause transmission until connectivity with an aeronautical ad-hoc network is available. Also, the results can support possible introduction scenarios for A2A data link technology, as they indicate, which coverage of data communication can be achieved for an equipped user in air traffic environments where only a fraction of all traffic participants are equipped with the same technology.

The presented results are subject to limitations though, since the transmission within the ad-hoc network was assumed to be ideal, without data overhead and delays due to organization of network establishment and data transmission within the aeronautical ad-hoc network. This would particularly affect the presented gateway data rates, which are expected to increase, if data overhead is considered. If more detailed transmission delay and transaction times yielding from a network simulation would be included, the data transmission would be more equally distributed over time, thus yielding more equally distributed data transmission rates with lower peak values (i.e. 99-percentile values). Also, some ADCD might not be within the aeronautical ad-hoc network coverage, if transaction times and data delays are reassessed, yielding a lower coverage of ADCD. Also, in this study only data rates at gateway aircraft assessed, while the highest data rates within an aeronautical ad-hoc network might also occur at bottlenecks within a cluster. Accordingly, the assessment of data rates at bottleneck aircraft is of high interest for further studies.

Furthermore, the underlying air traffic scenario is based on the situation in the North Atlantic oceanic airspace during a timeframe with high traffic density in 2019. The current air traffic situation, which has not yet fully recovered to pre-pandemic air traffic density, might relate to lower equipage fractions in the presented results.

6. Acknowledgements

The work presented in this paper was part of the project IntAirNet that was funded by the German Ministry of Federal Ministry for Economic Affairs and Climate Action (BMWK) under the National Aeronautical Research Program (LuFo) V-3 under the grant agreement no. 20V1708B.

7. Contact Author Email Address

mailto: alexander.hillebrecht@dlr.de

8. Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third-party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS proceedings or as individual off-prints from the proceedings.

9. References

[1] ICAO. *Global Air Navigation Plan*. *ICAO GANP Portal*. https://www4.icao.int/ganpportal/. Accessed 9 July 2021.

[2] SESAR Joint Undertaking. 2020. *European ATM master plan*. *Digitalising Europe's aviation infrastructure : executive view : 2020 edition*. 2020 Edition. Publications Office of the European Union, Luxembourg.

[3] Schnell, M., Epple, U., Shutin, D., and Schneckenburger, N. 2014. LDACS: future aeronautical communications for air-traffic management. *IEEE Commun. Mag.* 52, 5, 104–110.

[4] Medina, D. 2011. *Geographic load share routing in the airborne internet*. Ph.D. Thesis, Paris Lodron Universität.

[5] Sakhaee, E., Jamalipour, A., and Kato, N. 2006. Aeronautical ad hoc networks. In *IEEE Wireless Communications and Networking Conference, 2006. WCNC 2006*. IEEE, 246–251. https://doi.org/10.1109/WCNC.2006.1683472.

[6] Vey, Q., Pirovano, A., Radzik, J., and Garcia, F. 2014. Aeronautical Ad Hoc Network for Civil Aviation. In *Communication Technologies for Vehicles*, D. Hutchison, T. Kanade, J. Kittler, J. M. Kleinberg, A. Kobsa, F. Mattern, J. C. Mitchell, M. Naor, O. Nierstrasz, C. Pandu Rangan, B. Steffen, D. Terzopoulos, D. Tygar, G. Weikum, A. Sikora, M. Berbineau, A. Vinel, M. Jonsson, A. Pirovano and M. Aguado, Eds. Lecture Notes in Computer Science. Springer International Publishing, Cham, 81–93. https://doi.org/10.1007/978-3-319-06644-8_8.

[7] Ehammer, M., Gräupl, T., and Polo, E. 2011. AeroMACS data traffic model. In *2011 Integrated Communications, Navigation and Surveillance Conference (ICNS 2011)*. *Herndon, Virginia, USA, 10 - 12 May 2011*. IEEE, Piscataway, NJ, G5-1-G5-10. https://doi.org/10.1109/ICNSURV.2011.5935282.

[8] Eurocontrol and FAA. Communications Operating Concept and Requirements for the Future Radio System. COCR Version 2.0 2007.

[9] Gräupl, T. and Mäurer, N. 2019 - 2019. An Air Traffic Management Data Traffic Pattern for Aeronautical Communication System Evaluations. In *2019 IEEE/AIAA 38th Digital Avionics Systems Conference (DASC)*. IEEE, 1–6. https://doi.org/10.1109/DASC43569.2019.9081745.

[10] SESAR Joint Undertaking. 2015. *VDL Mode 2 Capacity and Performance Analysis*.

[11] SESAR Joint Undertaking. 2016. *VDL Mode 2 Measurement, Analysis and Simulation Campaign*.

[12] Vieira, L. F. M., Almiron, M. G., and Loureiro, A. A. F. 2011. 3D MANETs: Link Probability, Node Degree, Network Coverage and applications. In *2011 IEEE Wireless Communications and Networking Conference*. IEEE, 2042–2047. https://doi.org/10.1109/WCNC.2011.5779443.

[13] Marks, T., Hillebrecht, A., and Linke, F. 2022. Modeling air-to-air communication networks in the North Atlantic region (under review). In *CEAS Aeronautical Journal*. Springer International Publishing.

[14] Hillebrecht, A., Marks, T., and Gollnick, V. 2022. An aeronautical data traffic model for the North Atlantic oceanic airspace (under review). In *CEAS Aeronautical Journal*. Springer International Publishing.

[15] EUROCAE. 2007. Safety and Performance Standard for Air Traffic Data Link Services in Oceanic and Remote Airspace. ED-122. Oceanic SPR Standard.

[16] EUROCAE. 2011. Safety and Performance Standard for Air Traffic Data Link Services in Oceanic and Remote Airspace. ED-122 Change 1. Oceanic SPR Standard.

[17] EUROCAE. 2016. Safety and Performance Requirements Standard for Baseline 2 ATS Data Communications. ED-228A. Baseline 2 SPR Standard.