Improving the Lifespan of LDACS Air-To-Air Multi-Hop Connections by Heading Direction

Leonardus J.A. Jansen, Nils Mäurer, Thomas Ewert, Thomas Gräupl
Institute of Communication and Navigation
German Aerospace Center (DLR)
Wessling, Germany
leonardus.jansen@dlr.de

Corinna Schmitt
Research Institute CODE
Universität der Bundeswehr München
Neubiberg, Germany
corinna.schmitt@unibw.de

***Abstract*—The current capacity of aeronautical datalinks is reaching its limits, especially in the European airspace, and hindering the growth of global civil aviation. To modernize the Air Traffic Management (ATM) and digitize aeronautical communications, research, and deployment of successor technologies are underway. The planned successor for the En-Route (ENR) domain in European continental air traffic is the L-band Digital Aeronautical Communications System (LDACS) Air-Ground (A/G) terrestrial communications system. LDACS is planned to be expanded by an Air-Air (A/A) communication mode called LDACS A/A in the future. This long-distance multi-hop A/A communication can expand LDACS ground station coverage to oceanic and remote areas, thus enhancing the terrestrial infrastructure. While LDACS A/G incorporates robust cybersecurity measures, the development of cybersecurity for the LDACS A/A extension is in its early stages. This paper examines the stability of multi-hop connections over continental Europe based on historical flight data from the OpenSky Network and suggests that taking into consideration the heading of an aircraft can extend the lifetime of these connections. This increased connection lifetime makes the resource-demanding process of secure connection establishment worthwhile.**

***Index Terms*—LDACS A/G, LDACS A/A, Performance Evaluation, Cybersecurity**

I. INTRODUCTION

In recent years, the L-band Digital Aeronautical Communications System (LDACS) Air-Ground (A/G) datalink has emerged as a modern digital alternative to the analog Very High Frequency (VHF) aviation communication protocols. The LDACS A/G protocol is standardized in the Internet Engineering Task Force (IETF) [1] and currently undergoing standardization by International Civil Aviation Organization (ICAO) [2], [3]. It enables aircraft to securely connect to a ground station and exchange safety-critical data related to Air Traffic Management (ATM), including Air Traffic Control (ATC), Air Traffic Services (ATS), and ATC data. LDACS offers sufficient capacity for future applications like 4D trajectories. However, its use is limited to regions with deployed **GS!**s (**GS!**s). To establish secure digital connections over Oceanic, Remote, Polar (ORP) areas, an LDACS Air-Air (A/A) mode is required.

Nevertheless, LDACS A/A is still in its early stages, with only technical proposals available [4]–[6]. Previous research has explored the feasibility of ad-hoc mesh networks and routing strategies to optimize throughput such as [7]. However, only limited research has been conducted on the security aspects of LDACS A/A.

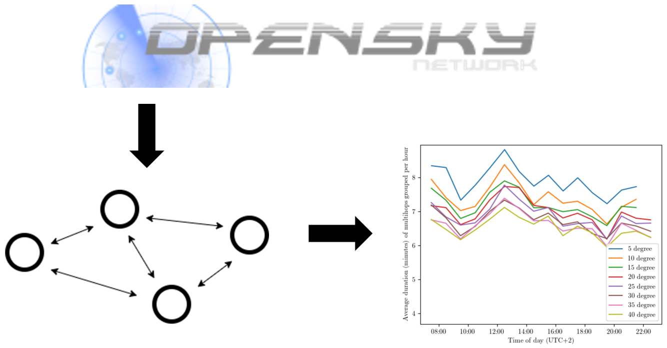

Fig. 1: Assessing Multi-Hop Connection lifespans from OpenSky Network Data [8].

In [9], we already counted the maximum amount of concurrent connections and established long-distance multi-hop connections with a maximum of 13 hops covering the north-south and east-west axes over Europe. However, this work was limited in the routing decision, since it did not take the heading of the aircraft into account.

This paper aims to identify more suitable routing algorithms and to evaluate the duration of stable air mesh-network connection over n-hops. Our analysis focuses on the theoretical lower bound of the required resources. Real air traffic data from Automatic Dependent Surveillance-Broadcast (ADS-B) is used to examine multi-hop routes over long distances, with aircraft acting as hops. Metrics such as the number of multi-hop connections and route stability over time are analyzed. This investigation provides insights into the feasibility of establishing secure connections within given time constraints, based on real flight patterns.

This paper is structured as follows: In Section II we present background information on the topic and present related work. Section III focuses on the applied methodology, which leads to the data analysis in Section IV. Based on gained insights Section V presents our discussion. Finally, the paper is concluded in Section VI.

II. BACKGROUND

In Section II-A, we discuss related work on Aeronautical Ad-Hoc Networks (AANETs). We provide background on the LDACS A/A mode in Section II-B and discuss path-finding algorithms in Section II-C.

A. Related Work

Routing in an AANET has been the subject of many publications. Most notably the ones by Medina et. al [7], [10], [11], in which the feasibility of routing traffic over the North Atlantic corridor is thoroughly investigated. Here, the idea of taking the heading information into account when making routing decisions was first introduced. Thus our investigation is based on his precursor work.

Later works by Kumar et al. [12] summarize routing algorithms for different types of flying ad-hoc networks, while more recently [13] introduced a cross-layered routing approach.

B. LDACS A/A

Developed by the German Aerospace Center (DLR), the LDACS A/A mode was first introduced by Bellido and Schnell et. al [4], with physical and Medium Access Layer (MAC) layer design almost completed in [6]. LDACS A/A will operate in the 960-1164 MHz band and thus has to share a part of the spectrum with Distance Measuring Equipment (DME) and Tactical Air Navigation (TACAN) in the aeronautical frequency band. In [6], restricting frequency planning to the north-east coast of North America, the North Atlantic Corridor, and western Europe, it was shown that it can operate in numerous frequency channels within the 960-1164 MHz frequency band without affecting the proper operation of DME and TACAN. In [5], it was shown that in terms of Medium Access procedure, generally speaking, a Self-organizing Time-Division Multiple-Access (STDMA)-based A/A data link performs better than the ALOHA-based A/A data link. For the physical layer, symbols are built either using Orthogonal Frequency-Division Multiplexing (OFDM) modulation and the Single-Carrier Frequency-Division Multiple Access (SC-FDMA), while Turbo Codes (TC) and Non-Binary Low-Density Parity-Check (NB-LDPC) codes for air-ground aeronautical communications were all proposed in [4].

In terms of cell size, a radius of 200 Nautical Miles (NM) around each aircraft is assumed and mostly broadcast-based services, such as ADS-B are foreseen as use cases for the LDACS A/A mode [4]. Please note, the 200 NM is also the radius assumed for further computations in this work.

Another use case of the LDACS A/A is forming point-to-point connections with other aircraft and thus forming an AANET. This is also the focus of this work. Please note, that in terms of latency, assuming similar latency times for data transmission as the LDACS A/G mode offers [14], every connection with more than three hops likely has a longer latency than SatCOM [15]. Thus in this work, only 1-, 2- and 3-hop connections are investigated.

C. Thoughts on Different Algorithms

The data we present in Section III are flight traces based on latitude, longitude, and time. This allows us to construct graphs and paths among the nodes which in turn are represented by aircraft at a certain moment in time. Given the pre-processed set of graphs over time (i.e., knowing the one-hop connections for all aircraft), there are considerations on how to effectively select an algorithm to find multi-hop routes. Here we discuss suitable options, namely Dijkstra's algorithm [16], the Floyd-Warshall algorithm [17], and Breadth-First Search [18].

First introduced by Edsger Dijkstra in 1959 [16], the **Dijkstra algorithm** is an algorithm that is used for finding the shortest path between nodes in a weighted graph, assuming no negative-weight circles exist. It calculates the shortest path from one single node to eventually all other nodes in the graph.

The algorithm is easy to implement and it is guaranteed to find the shortest path. However, we would need to actively keep track of how many hops it took to get to a certain vertex, as the Dijkstra algorithm's priority queue is sorted on distance, not on the number of hops.

The so-called **Floyd-Warshall algorithm** introduced by Robert Floyd in 1962 [17] calculates the shortest distance from all nodes to all other nodes within a graph. This could be a strong performance improvement as opposed to the Dijkstra algorithm, which has to be run once for every starting node. However, the Floyd-Warshall algorithm does not keep track of the paths, which are important in this work because we need to keep track of how long the connection holds throughout time.

First introduced by Edward Moore in 1959 [18], the **Breadth-First Search (BFS)** algorithm is a search algorithm that is used on search trees and uses a queue for deciding the next node to explore. It can also be used on (cyclic) graphs if the nodes that have been visited are being tracked. In a cyclic graph, however, it does not necessarily find the shortest path between two nodes.

For example, we want to find a route from node A to node E in the graph shown in Figure 2. Node C is just within reach of A and E, but D and B are not, respectively. The weight of the edges is equal to the Euclidean distance between the respective nodes. Both the Dijkstra algorithm and Floyd-Warshall algorithm would find the shortest path from A to E through B and D. BFS, however, does not sort its queue by accumulated weight, but simply by order of encounter. As a result, it will explore node C before exploring node D and therefore return a path from A to E through C. The BFS algorithm thus does not optimize on the path length but on the number of nodes. For this work, this is preferred, as one of the major resource constraints is the secure connection establishment time. This time is mainly affected by the number of hops, not by the distance between them. Additionally, the

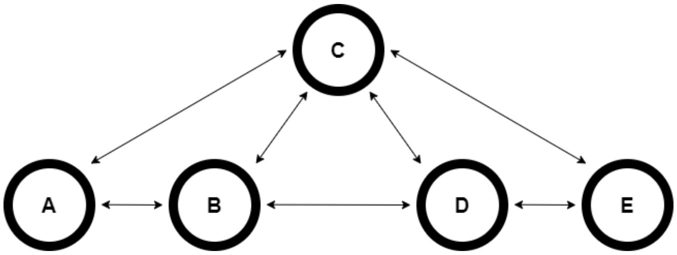

Fig. 2: A graph in which BFS does not find the shortest path between nodes A and E.

BFS algorithm can easily be terminated as soon as the three-hop limit, which we set for this work, is reached, which makes it a suitable choice for implementation. Because of this and BFS's ability to optimize the number of hops, BFS is our algorithm of choice for this work.

III. METHODOLOGY

We look at En-Route (ENR) flights and classify the air traffic (e.g., heading, number of aircraft). We calculate all potential 1-hop connections and use these results to calculate a selection of 2- and 3-hop connections based on different maximum heading deviation settings. We then determine if the duration of these connections justifies the overhead associated with a secure connection establishment.

A. *OpenSky Data*

The research community relies on the OpenSky database, which offers flight data generated by ADS-B and Mode S. EUROCONTROL provides aggregated information on Instrument Flight Rules (IFR) flights per year, which was consulted to identify notable days in European air traffic and create various traffic forecast scenarios for the future years. The year 2019, recognized as the busiest year for air traffic thus far, specifically the 28th of June 2019, was chosen as the busiest day in the history of European civil aviation, with 37,228 unique flights [8], [19]–[21].

The OpenSky Network offers data in different formats, including aggregated per flight, flight state, and unprocessed raw data, with precise timestamp updates provided at one-second intervals. This versatility makes the data a perfect fit for our requirements. We focused our analysis on the region where aircraft will initially be deployed, within latitudes 34 degrees North and 70 degrees North, as well as longitudes 11 degrees West and 30 degrees East, corresponding to Europe [14].

Since the position reports in the OpenSky Network database were not assigned to specific flights, we developed a pre-processor with predefined rules to extract individual flight paths.

- A flight starts, when the first record of an aircraft's ICAO 24-bit address is detected.
- A flight ends, when the aircraft reports *on ground*. Alternatively, if no position report within 15 minutes has been received, the flight is ended as the *on ground* message might not have been received due to e.g., shadowing of the signal near the ground.
- As the operation area of aircraft is the ENR, only flights reaching an altitude over 10,000 ft are considered.

Due to incomplete traces or flight positions outside our selected area, e.g., in Turkey or Ukraine, of the 37,228 roughly 32,000 complete traces remained for the next computations.

The aircraft traces are given in second granularity, however, the flight traces can have time gaps where no position record was available. For this case, we interpolated the location of an aircraft if there was a gap of more than 60, but less than 600 seconds. If an aircraft has not updated its position for more than a minute, but some time later, we assume a straight line within those positions. However, if there is no new location data for more than 600 seconds, we assume that the aircraft trace is terminated at the last known position.

B. *Preprocessing*

At first, the OpenSky data was preprocessed and formatted into `csv` format. This revealed numerous holes in the data. Such holes included missing headings, missing altitudes (barometric, GNSS, or both), or even gaps with data points completely missing for an aircraft for a few minutes. While most of the ADS-B enabled aircraft send location data every few seconds, entries in OpenSky do not show this pattern. The reason for this behavior is quite simple: OpenSky relies on radio amateurs to capture the ADS-B data and not every point in Europe is covered. Thus, the flight traces captured have these missing data points as mentioned above.

To deal with these gaps, we employ **interpolation** to have sufficient data points to simulate the multi-hop connections more realistically over time. Artificial position data was added between two data points that were more than 1 minute apart. Data points whose interval was greater than 10 minutes were excluded from the interpolation. A straight line was defined between the two data points whereby the aircraft's heading would remain constant along said line.

To ensure the accuracy of our simulations, every data point is required to have a **heading**. To ensure this, any data points without a heading were complemented by calculating the heading between the previous and current data points. The results of our simulations rely significantly on the heading of aircraft, as it is the primary variable in the decision-making during connection establishment, as we expect the resulting network stability over time to be relying on this variable.

The focus of our work is on aircraft that are airborne. Therefore, the data is filtered to exclude all aircraft that are below FL 100.

C. *Simulation*

The simulation of time in the `flynalyzer` module (c.f. Figure 3) occurs in 1-second intervals, which is the same granularity as the original data. For every second, three processes are executed: 1) newly activated flights are

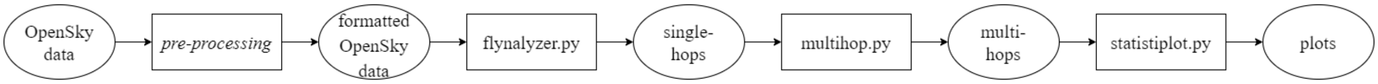

Fig. 3: Our Data Pipeline for the OpenSky Network Data.

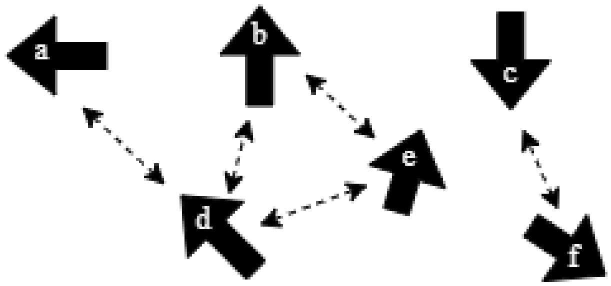

Fig. 4: Schematic example of Aircraft and their potential one-hop connections with up to 40 degrees heading deviation.

introduced, 2) existing flights are updated, and 3) flights that have surpassed their maximum interval after interpolation (i.e. $>$ 60 seconds) are deactivated.

At every 10-second interval, the system calculates a 'snapshot' of all possible **1-hop connections** between aircraft. The latest known position of each aircraft at that moment is used. First, all existing connections are checked for whether they can still exist (i.e., whether the distance between the two aircraft is still $<$ 200 NM). Then, all possible new 1-hop connections are calculated. For a new connection to be possible, the distance must be less than 200 NM and the difference in heading must be less than 5,..,40, degrees, with "difference in heading" the parameter being tested for. An example of aircraft and their potential 1-hop connections in the case of a 40-degree limit is shown in Figure 4. The bold arrows represent aircraft and their heading. Dashed arrows represent potential 1-hop connections. In this example, aircraft b can only connect to aircraft d and e, but not to a, as the difference in headings with aircraft a exceeds 40 degrees. The difference in heading is only taken into account when creating a new connection, but not when assessing the validity of existing connections, as this would be unnecessarily counterproductive.

Connections that are no longer possible will not be deleted, but are moved into an archive, which forms the output of the simulation and is used in the next module. The archive is therefore saved to a file using the `pickle` library [22]. The connections are stored as a collection of undirected graphs, with one graph per 10-second interval representing the snapshot of all 1-hop connections existing at that moment in time, based on the heading angle and the distance between the aircraft. Specifically, the connections are saved as dictionaries of the nested type {`time:int : `{`icao24:str : `{`icao24:str : connection:Connection`}}} where `time` is the timestamp of when the connection began, `icao24` is the ICAO 24-bit identifier of the aircraft, and `Connection` is a custom class described in Listing 1.

Listing 1: Connection class

```
class Connection:
    icao24_a: str
    icao24_b: str
    starting_time: int
    ending_time: int
    path: [str]
```

By saving the connections in a dictionary sorted by start time, it becomes easy to reuse the data. Additionally, by sorting them on the two respective aircraft, the starting and ending nodes, every connection can be accessed in two ways; by a starting node followed by the ending node, or vice versa. Furthermore, since the connections are a class, they are automatically saved by reference in a Python dictionary, meaning the connection itself is stored in memory only once.

The next step in the simulation pipeline is to load the snapshots of 1-hop connections and re-use them to compute **multi-hop connections**. The snapshots have been taken every 10 seconds and therefore the multi-hop calculation is also done in 10-second intervals. In the simulation, the following steps are executed at every interval: 1) activation of new single-hop connections, 2) removal of old single-hop connections, 3) removal of old multi-hop connections, and 4) finding new multi-hop connections. As explained in Section II-B, we only consider connections of up to three hops due to the latency of SATCOM likely becoming better than communicating over more than three LDACS A/A hops. To determine the routes between the aircraft, we evaluated BFS [18], the Dijkstra algorithm [16], and the Floyd-Warshall algorithm [17]. BFS was chosen due to its ease of implementation and its optimization of the number of hops. The considerations on these algorithms are further explained in Section II-C. 200 NM is assumed for the LDACS A/A cell size.

Due to the complexity of computing all possible 3-hop connections between all aircraft, we limited the number of aircraft for which to calculate all possible routes. At every interval of 10 seconds, thus for every snapshot of the 1-hop connections, 5 aircraft were randomly selected and all possible 2-hop and 3-hop connections from those roots were calculated. This reduced the run-time complexity by a factor `n`, with `n` being the number of aircraft in the simulation. The newly determined multi-hop connections are then added to the current multi-hop connections and are stored for viability at every interval. As with single-hop connections, any multi-hop connections no longer possible were not deleted but rather

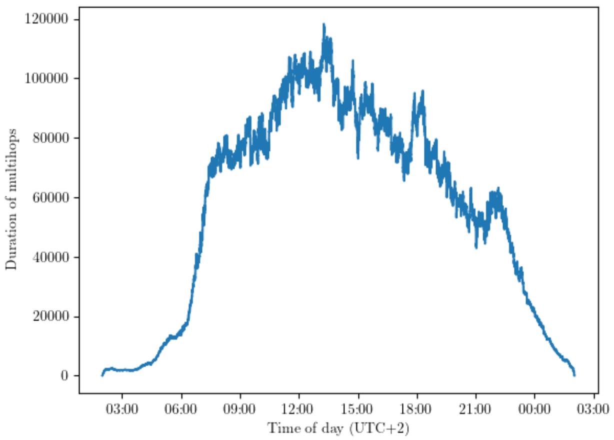

Fig. 5: The number of 2-hop connections over the complete day with a maximal heading deviation of 5 degrees.

added to an archive and saved to a file using the `Pickle` library.

D. *Visualization*

The computational complexity of computing single- and multi-hop connections necessitates the saving of intermediate results to files. The last step of the data pipeline (as shown in Figure 3) is the fastest, wherein the saved multi-hop connections are loaded from the file and replayed by simulating time and activating and deactivating the connections. The relevant statistics are computed and saved for each interval and are plotted at the end. The process of loading the data from the file into RAM takes longer than the computation and plotting.

In the next Section IV, we present the results and plots from all steps of the data pipeline.

IV. RESULTS

In Section IV-A, we discuss our selection of the 8 AM to 10 PM time frame in which to calculate average multi-hop connection lifespans. The durations of the connections are presented in Section IV-B.

A. *Evaluating a Relevant Time Frame*

Figure 5 shows the number of 2-hop connections over the complete 24-hour time frame. We see that before 8 AM and after 10 PM there are significantly fewer multi-hop connections, despite choosing the same amount of aircraft at every interval to calculate all possible multi-hop connections from, as described in Section III-C. This is because during the night there are much fewer aircraft in the air and therefore the potential mesh network is sparse. As a result, the average time a multi-hop connection is alive, fluctuates much more in the nighttime than during the day, which makes it harder to see the influence of the heading deviation as a variable. Therefore, in Figures 6 and 8 we show the average connection times from 8 AM to 10 PM only.

B. *Stable Connection Duration*

Figures 6 and 8 show the average duration of 2-hop and 3-hop connections respectively per hour and degree. The figures are plotted on the same axes for comparability. As expected, 2-hop connections stay alive longer than 3-hop connections. We see in both figures, that the connections with aircraft having a smaller heading deviation hold longer. The lines are stacked in the same order as the heading deviation they represent.

We see that for the 2-hop connections, the average connection times vary from ca. 8 minutes with up to 5-degree deviation to ca. 6.5 minutes with up to 40-degree deviation. For 3-hop connections, the average connection times vary from almost 5 minutes with up to 5-degree deviation to a bit more than four minutes with up to 40-degree deviation.

Figures 7 and 9 show the average connection time per deviation degree setting over the complete day. These figures show that connections between aircraft that fly roughly in the same direction do indeed hold longer on average. The average duration of 2-hop connections ranges from 8.1 minutes with up to 5-degree heading deviation to 6.7 minutes with up to 40-degree heading deviation. The average duration of 3-hop connections ranges from 4.8 minutes with up to 5-degree heading deviation to 4.2 minutes with up to 40-degree heading deviation. It is important to note that all connections in one group with a specific maximum degree deviation setting are also present in the group with a higher deviation, but not the other way around. For example, all connections in the 5-degree group are also present in the maximal 40-degree group, but not the other way around. That's why the curve is flattening out instead of being more linear.

Concluding, Figures 7 and 9 confirm findings in Figures 6 and 8 and present a concise picture of the average stable connection duration per heading normalized over the entire 24 hour period.

V. DISCUSSION

Our results suggest that if a multi-hop connection to an aircraft is necessary, a maximum lifespan of up to 8 minutes for 2-hop and a maximum of 5 minutes for a 3-hop connection is to be expected. These connection times allow to create a secured connection, which involves additional latency and data overhead due to additional data transmissions, given that a connection needs to be established within 10 seconds and the average expected lifespan of the connection is up to 8 minutes.

Secure air-to-air connections can also be used by aircraft to improve trajectory planning in real-time. One application, in dire need of such an AANET, is the Airbus fello'fly technology. This technology allows aircraft to fly in less than one-mile separation and thus enables the following aircraft to use the WAKE vortex of the preceding one to drastically reduce fuel consumption. However, at the time of writing, fello'fly is supposed to be supported by insecure ADS-B broadcast transmission, posing a severe security and safety risk as shown by Ewert et al. in [23].

In [24], Zheng et al. proposed the use of aircraft heading in the routing protocol to increase the lifespan of the resulting

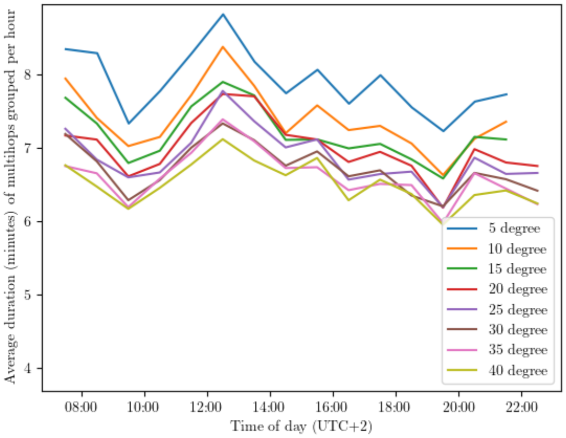

Fig. 6: Average duration of 2-hop connections during the day per maximum heading deviation.

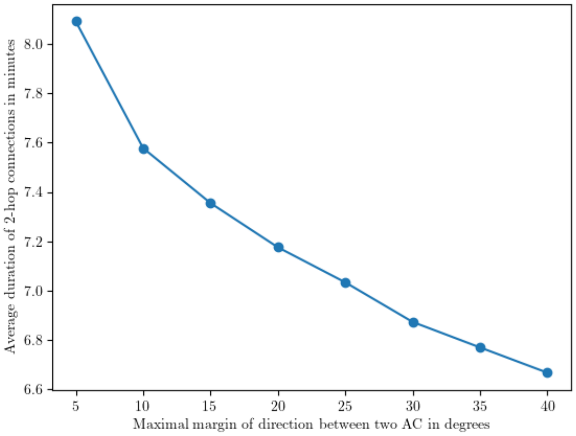

Fig. 7: Average 2-hop connection time over a complete day per maximum heading deviation.

multi-hop connection. However, their evaluation was limited to artificial data. In this work, we evaluated the effectiveness of this feature using real historical flight data, thus providing a more realistic view of the potential impact of its implementation in production.

The results of this work provide a basis for an informed decision for the next hop in a multi-hop connection. We found that even when aircraft are only remotely traveling in a similar direction, the duration of the connection is sufficient for a resource-heavy secure connection establishment process.

This research was conducted in the context of an isolated ad-hoc network without ground stations. Future work will focus on air-to-air connections to extend the reach and coverage area of dedicated ground stations.

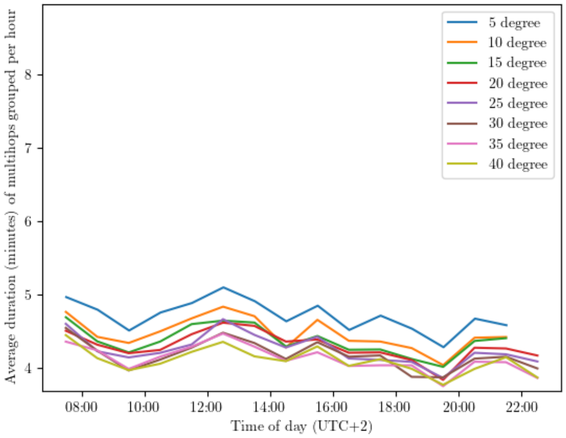

Fig. 8: Average duration of 3-hop connections during the day per maximum heading deviation.

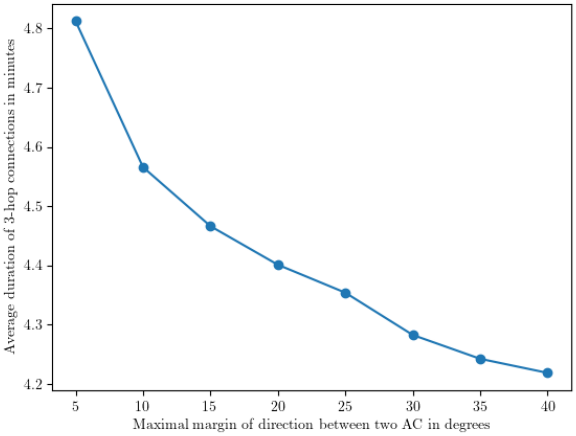

Fig. 9: Average 3-hop connection time over a complete day per maximum heading deviation.

VI. CONCLUSION

With the growth of air traffic density, and as a backup option for SatCOM or terrestrial data-link outages, an air-to-air network, an AANET, could provide a great addition to the existing aeronautical data-link ecosystem. One possible candidate is the LDACS A/A mode. The LDACS A/A has two distinct use cases: (1) broadcasting data to flying neighboring aircraft and (2) forming a multi-hop network to securely transmit data in a point-to-point fashion from one aircraft to its destination. Previous work in [9] showed these connections to be very short-lived, posing the question of whether it is feasible to establish a secure connection over multiple hops, given that the secure connection establishing process requires time and resources. This work investigated the duration of 2- and 3-hop connections. The hop limitation was deliberately chosen since it is expectable that the latency of a SatCOM connection becomes better after 3-hops. This research concludes that taking the heading of aircraft into account when computing the packet routes can result in a connection duration improvement by up to 20%, comparing 40° to 5° heading differences. Additionally, the average stable connection duration for a 2-hop connection was found to be seven minutes, and the average stable connection duration for a 3-hop connection was found to be four and a half minutes.

This paves the way for future work identifying suitable cryptographic methods in securing broadcast and multi-hop connections and is a first step in identifying suitable routing algorithms for AANETs.

ACRONYMS

A/A	Air-Air
A/G	Air-Ground
AANET	Aeronautical Ad-Hoc Network
ADS-B	Automatic Dependent Surveillance-Broadcast
ATC	Air Traffic Control
ATM	Air Traffic Management
ATS	Air Traffic Services
BFS	Breadth-First Search
DME	Distance Measuring Equipment
ENR	En-Route
ICAO	International Civil Aviation Organization
IETF	Internet Engineering Task Force
IFR	Instrument Flight Rules
LDACS	L-band Digital Aeronautical Communications System
MAC	Medium Access Layer
NB-LDPC	Non-Binary Low-Density Parity-Check
OFDM	Orthogonal Frequency-Division Multiplexing
ORP	Oceanic, Remote, Polar
SC-FDMA	Single-Carrier Frequency-Division Multiple Access
STDMA	Self-organizing Time-Division Multiple-Access
TACAN	Tactical Air Navigation
VHF	Very High Frequency

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