Aeronautical ad hoc networks : a new datalink for ATM

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***Abstract*—The increase in air traffic and the use of digital communications in ATM create a need for new communication solutions. In this article, we present an aeronautical ad hoc network which could be used to meet those needs. Being self configured, self healing and not needing a heavy ground infrastructure, such networks are cost-efficient and performant ways to transmit data between ground and aircraft. In the design of such a communication architecture, we used our own simulation tool to test the system and its performances which are promising. Both the physical and link layer are covered in our study, as well as the impact of path selection at the network level on the performance of the network as a whole.**

I. Introduction

A. Problem Statement

Future aeronautical communications are expected to face a great challenge in the next ten years. In the context of an increasing number of aircraft traffic, the ratio of digital data communication will increase relatively to voice radio communications, with the deployment of recent applications such as CPDLC (Controller Pilot Data Link Communications). On the other hand, new ATS or AOC applications will certainly be proposed and provided as answers to the main actor's expectation. Theses new applications, such as those dedicated to weather advisories broadcast, will need a large amount of communication resources. The rapid growth of air traffic demands a new communication infrastructure with increased bandwidth, high speed services and applications to satisfy expected air-ground communication requirements.

This migration has started and in order to prevent communication links congestion and thus provide the needed resource, some new system have been studied and/or partially deployed for both ATS and AOC. Some of these recent system, such as VDL mode 2 or LDACS-2, are based on direct ground station access implying an exclusively use in terrestrial domain. The throughputs these systems offer from the ground to an aircraft in line-of-sight are respectively 31.5 kbps and 275 kbps. Satellite-based communications are proposed as the solution for aeronautical communication in oceanic aera. Current satellite based communications architectures offer an amount of tens kps of capacity. Future solutions should offer more resources. For instance, the most recent SwiftBroadband solution by Inmarsat proposes an IP-based packet-switched service that provides a symmetric data connection of up to 332 kbps over an intermediate gain antenna.

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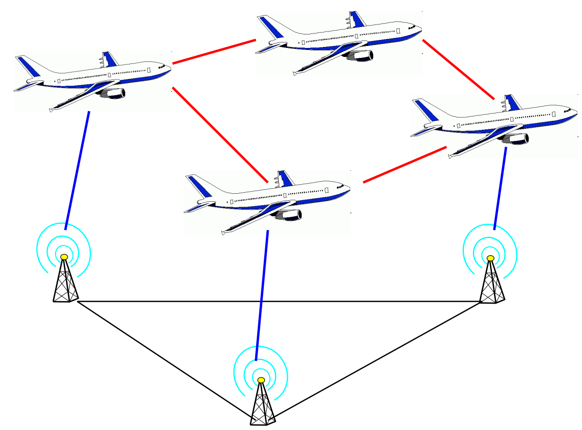

Figure 1. Topology of an aeronautical ad-hoc network

Nevertheless all those solutions show limits in terms of achievable throughput and/or coverage, which motivates the need for a new class of solution.

B. An aeronautical ad hoc network as a new data-link

1) Presentation: Our system relies on an aeronautical ad hoc network, the idea of such networks is to introduce wireless connections between aircraft, each being able to establish a connection with other aircraft nearby. Such a network does not need a heavy ground infrastructure and is self configuring and self healing. Each aircraft in the network can forward traffic to another aircraft or to a ground station, and therefore act as a router to transport data hop by hop to the destination. Hence, no centralized administration is needed to route exchanged data. Figure 1 represents the topology of such a network.

2) Related work: Some projects have already studied aeronautical ad-hoc networks. Among these, the ATENAA Project [1], [2] which began in 2004, deals with an aeronautical ad-hoc network which uses both directionnal and omni-directionnal antennas. The directional antennas are used to provide high throughput between aircraft, at the cost of dealing with the problem of pointing and tracking an aircraft in flight. Omni-directional antennas on the other hand, are used to send the signalisation and to detect aircraft in the area. The NewSky Project [3] which began in 2007, studies the feasibility of a global aeronautical network including all the means of communications of an aircraft, even connections between two aircraft, to transport all data for the air traffic control, the airlines and passengers.

3) Challenges: An aeronautical ad-hoc network brings up many issues that have to be considered. Firstly, there are issues at the physical and data link layers for the connection between aircraft, and between an aircraft and ground stations. Then, there are issues at the network layer because the network, due to the high speed of aircraft, may have a very dynamic topology, which could be a problem for the routing protocols.

In this paper, we aim at studying the feasibility of an aeronautical ad-hoc network with the aircraft flying over the French sky. We consider a graph, whose nodes are the aircraft, and whose edges are the connections between them, and we check that this graph is as highly connected as possible. We also want to estimate the percentage of connected aircraft during a day. First, we present the simulation tool we have developed. And, as we need accurate information on the air traffic during a significant duration, we present the aircraft position data. Then, we focus on the link between aircraft. And, finally, we present the performances of our communication architecture.

II. Aeronautical Ad Hoc Network Simulation Tool

A. Software Architecture

Figure 2 shows the principle of the software we have developped for this study. This software has been writen in JAVA. It is a simulation tool for aeronautical ad hoc network and more generally for wireless ad hoc network. This software needs some inputs :

- the ground stations positions
- the link budget of the connections in order to have the maximum range of each aircraft and each ground stations, and the maximum available throughput for each connections
- the positions of aircraft

Then, we can compute for example the percentage of connected aircraft, the available throughput of each aircraft, the interference level. Moreover, we have made some visualisation to show the aeronautical ad hoc network. Figure 3 shows a screenshot of our software.

B. Input data

1) Aircraft position data: In [4], [5], [6], the study of the feasibility of an aeronautical ad-hoc network is based on a statistical approach of the number of flights in an area. They infer the density of aircraft and then, by using a Poisson distribution, they obtain the probability of having at least n planes in an area around the aircraft. The probability of forming an aeronautical ad-hoc network is then the probability of always having at least two aircraft in a sphere whose radius is the optical range. In [7], the feasibility study is based on a list of flight plans. Trajectories are interpolated between departure and destination airports with great circle arcs, which are actually the shortest paths between two points of the Earth

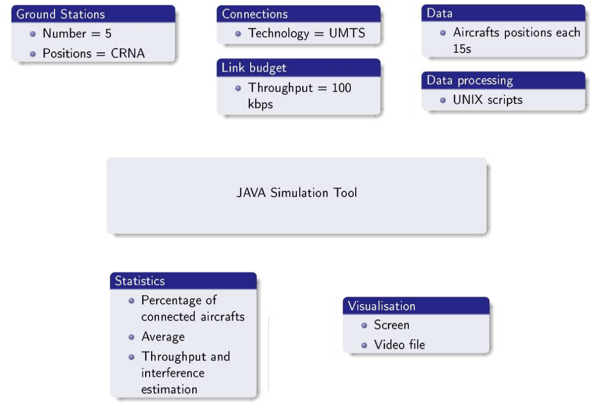

Figure 2. Software principle

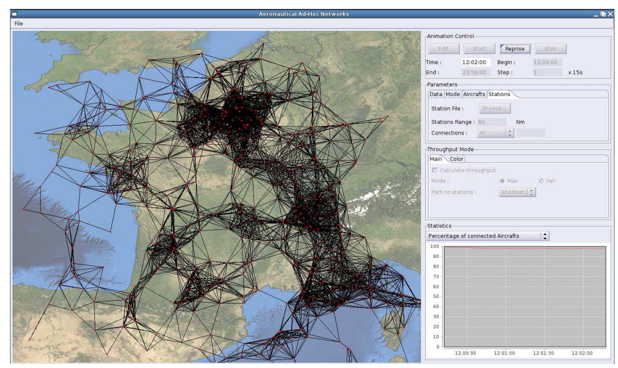

Figure 3. Screenshot of our simulation tool

sphere. For the present study, sources data on flight plan have been provided by the DSNA (Direction des Services de la Navigation Aérienne). These data give the position of aircraft flying through a considered geographic area, each 15 seconds during a given day.

2) Parameters: Our software needs some parameters to simulate the aeronautical ad hoc network. First, we need the maximum range at which two aircraft can establish a connection. Then, we need some parameters about the ground stations : their positions and their range.

C. Software Outputs

The software computes all available connections between aircrafts and is able to plot them on the screen. Then, we can compute the percentage of connected aircrafts. Finally, the software can compute the available throughput and the interference level of each aircrafts and provide some statistics.

III. Physical and Link Layers

A. Inter-aircraft links

1) Choice of technology: First of all, a wireless technology is needed for the links between aircraft, and between aircraft and ground stations. We studied existing technologies, such as Wi-MAX and UMTS. Wi-MAX uses SOFDMA (Scalable Orthogonal Frequency-Division Multiple Access), whereas UMTS uses W-CDMA (Wideband Code Division Multiple Access). However, the Wi-MAX time and frequency division multiplexing might reach its limits because of the high density of aircraft in some areas (e.g. around big European hubs), and a frequency reuse plan is beyond the scope of our study. A code-division multiplexing appears to be better for our system. Indeed, this will allow us to identify each aircraft by a different code. Thus each aircraft would be able to communicate with several aircraft simultaneously.

2) Link Budget: In [4], [5], [6], it is considered that a connection can be established between two aircraft if they are in optical range. In our case, we want to guarantee that the connection has a minimum throughput of 100 kbps. That is why we have to make a link budget of the connection to find the maximum distance that guarantee this minimum throughput. It is to be noted that in general, aircraft will be closer than the maximum distance, and therefore the throughput will be higher than 100 kbps.

In [8], we can find a standard link budget for UMTS connections between a station and a mobile phone. We have changed some of the parameters of the UMTS technology to improve the throughput available for the user in our context.

First, we consider a chip rate of 20 Mcps, to be compared to 3.84 Mcps for UMTS. It means that we have a processing gain of

$$10.log\left(\frac{throughput_{chip}}{throughput_{data}}\right) = 23dB.$$

Then, we assume the use of omnidirectional antennas for aircraft with 1 W emission power. Finally, we consider an interference margin of 3 dB. The resulting link budget is shown in table I.

3) Propagation model: The maximum free space loss acceptable to guarantee a minimum throughput of 100 kbps for each connections is 142.02 dB. To find the distance corresponding to this maximum loss, we have to choose a propagation model. In [9], we can find some studies about UMTS performances in normal conditions, that is for a connection between a ground station and a mobile phone. The simulations parameters are the difference of altitude between the station and the mobile phone, the vegetation characteristics, the average height of the buildings, ... These won't apply to our study, as connections between aircraft will be in direct line-of-sight, and if we ignore the atmosphere attenuation, we can use a propagation model in free space.

So we have

$$A = \frac{\lambda^2}{(4\pi d)^2},$$

where A is the free space loss in dB, λ the wavelength in m and d the distance in m. Which leads to:

$$A_{dB} = 32.44 + 20log(f_{MHz}) + 20log(d_{km}).$$

For several frequency values, we obtain the distance shown in table II.

We can see that at 2 GHz, which is a frequency close to the frequency used by the UMTS technology, an aircraft can establish a connection with an other aircraft if the distance between them is shorter than about 150 km. But this distance is very dependant on the frequency, which is yet to specify. That is why the maximum distance between two aircraft for the establishment of a connection will be a parameter of our simulations, as in [7].

Table II
MAXIMUM DISTANCE BETWEEN TWO AIRCRAFT (100 KBPS)

Free space losses (dB)	142.02	142.02	142.02	142.02
Frequency (GHz)	2	3	4	5
Distance (km)	150.65	100.43	75.33	60.26

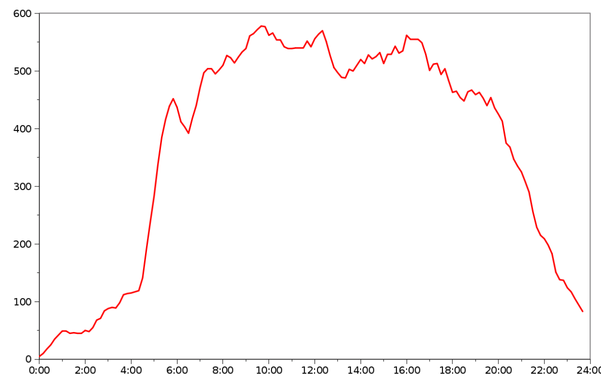

Figure 4. Number of inflight aircraft

B. Influence of the communication range

In this part, we present our results for a day of June 2007. This day, 9435 aircraft have flown over the French territory and we have their positions each 15 seconds for all the day. Figure 4 shows the number of in-flight aircraft across the day.

We can distinguish two different periods : the first one between 6 a.m. and 9 p.m. where the air traffic is dense; and the second one covering the rest of the day where there are always less than 200 aircraft in the sky. During this last period, it is obvious that it will be difficult to maintain the service for all aircraft.

We make the assumption that the ground stations will be placed near the five french CRNA (Centre en Route de la Navigation Aérienne), whose positions have been chosen by the ATC administration to fairly share the amount of in-flight aircraft.

The first simulation results highlight the influence of the maximum distance between two aircraft to establish a connection on the percentage of connected aircraft. In figure 5, we can clearly see that the longer the range is, the higher the percentage of connected aircraft will be.

Table III shows the average percentage of connected aircraft during the whole day and between 6 a.m. and 9 p.m.

We underline the fact that for a range longer than 125 km, more than 90% of aircraft are connected. Between 6 a.m and 9 p.m., even a 100 km range is enough to connect more than 95% of aircraft.

These results are promising, but not all aircraft are connected, even for a range of 150 km. Actually, what we have observed is that during the night, unconnected aircraft can be found everywhere in the area we consider, because the aircraft density is not high enough to guarantee a connected

Transmitter		
Throughput (kbps)	x	**100**
Maximum emission power (W)		**1**
Mawimum emission power (dBm)	a	30
Antenna gain (dBi)	b	0
EIRP (dBm)	$c = a + b$	30
Receiver		
Noise density (dBm/Hz)	d	-174.00
Receiver noise (dB)	e	5.00
Receivernoise density (dBm/Hz)	$f = d + e$	-169.00
Receivernoise power (dBm)	$g = f + 10 * log(chip)$	-95.99
Interference margin (dB)	h	3.00
Receiver interference power (dBm)	$i = 10 * log\left(10^{\frac{(g+h)}{10}} - 10^{\frac{g}{10}}\right)$	-96.01
Global effective noise + interference (dBm)	$j = 10 * log\left(10^{\frac{g}{10}} - 10^{\frac{i}{10}}\right)$	-93.01
Treatment gain (dB)	$k = 10 * log(chip/x)$	23.01
Eb/No (dB)	l	3.00
Receiver sensibility (dBm)	$m = l - k + j$	-113.02
Receiver antenna gain (dBi)	n	0.00
Cable loss (dB)	o	1.00
Free space loss (dB)	$p = c - m + n - o$	**142.02**

Table I
LINK BUBGET

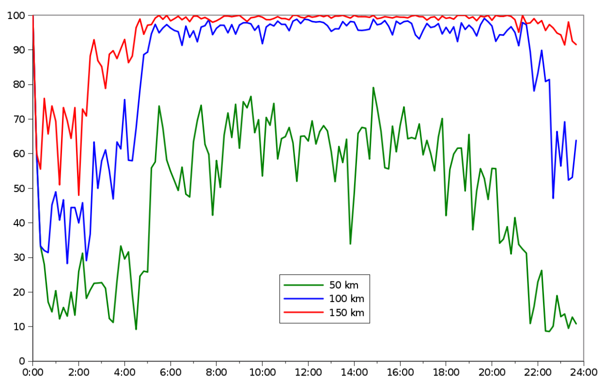

Figure 5. Range Influence

Range (km)	Average ratio (%) of connected aircraft between 0 a.m. and 12 p.m.	Average ratio (%) of connected aircraft between 6 a.m. and 9 p.m.
50	47.55	59.97
75	73.61	89.68
100	84.63	96.50
125	91.00	98.69
150	94.72	99.41

Table III
RANGE INFLUENCE

network. One solution to connect them would be to increase the communication range of each aircraft, even if it leads to throughputs lower than 1 Mbps. Though, as there will be few aircraft, this throughput might be enough. During the rest of the day, the density of aircraft is higher and it is easier to achieve network connectivity. We noticed that, during this period, all unconnected aircraft were located on the edge of the area we study, meaning that they would probably be connected if we considered aircraft flying in Europe.

C. Ground stations position

A study on ground stations position has been made in order to maximize the offered capacity to each aircraft and the network connectivity and to minimize the number of deployed ground stations. Intuitively, it seems obvious to choose for ground stations the areas with high mean density of aircraft to offer the needed resources in such important points. On the other hand, it could also be an advantage to choose ground stations positions in area with low density of aircraft to maximize the ad hoc network connectivity. That is why such a study has been made. As in the study of the influence of the communication range, our results were based on the positions each 15 seconds of the aircraft which have flown in the french sky during a day of june 2007. Two main approaches have been applied. The first has consisted of empirically defining the positions of one to five ground stations. And the second one has consisted in splitting the French area in a 3 x 3 matrix and studying exhaustively all the scenario with one to five ground stations with a maximum of one ground station per sub-area. Finally, a second step of this last approach has consisted in refining ground stations positions in each subarea with a new splitting of each subarea in a 3 x 3 matrix and the same approach for the best positions obtained during the first step. In these two approaches, for each combination the connected aircraft ratio and the mean offered capacity to each node have been estimated using our software.

The obtained results show that in order to cover the French sky, 3 ground stations at least should be necessary. But for all considered combinations, the two approaches show the same global result : the low impact of ground stations positions on the connected aircraft ratio and the mean offered capacity to each node. Each time the results were very near those obtained with our first study in which ground stations have been positioned near the five french CRNAs. Considering that in our study the density of aircraft at different geographical

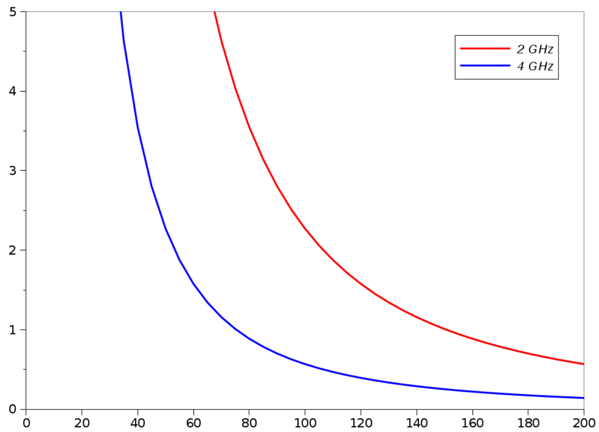

Figure 6. Throughput (Mbps) evolution with the distance (km)

positions is relatively homogeneous, such a result does not come as a surprise. It is to be noted that these conclusions should not be extended to other geographical contexts.

IV. Path Selection

To determine the available throughput per aircraft, a path to the ground station has to be chosen. As the routing protocol is not yet defined, we use the shortest path to the closest ground station, given by the Dijsktra algorithm. We obtain a list of edge representing the path from each aircraft to the ground station. Then, we will present two approaches to estimate the available throughput per aircraft.

A. Maximum available throughput per aircraft

The first approach is to determine the maximum throughput for a given aircraft. For this, we consider that only this aircraft is sending messages. With the Dijsktra algorithm, we have obtained a path to the ground station. And with the length of each edge of this path, we can determine the available throughput on each link. We use the link budget and the free space propagation model, which gives the two following equations:

$$A_{dB} = 142.02 - 10 \cdot log(throughput_{Mbps})$$

$$A_{dB} = 92.44 + 20 \cdot log(f_{GHz}) + 20 \cdot log(d_{km})$$

We have :

$$throughput_{Mbps} = 10^{\frac{49.58 - 20 \cdot log(f_{GHz}) - 20 \cdot log(d_{km})}{10}}$$

And finally :

$$throughput_{Mbps} = \frac{10^{4.958}}{f_{GHz}^2 \cdot d_{km}^2}$$

Figure 6 shows the evolution of the throughput with the distance for two frequencies.

Theoretically, the throughput decreases in $\frac{1}{x^2}$ with the distance. But even if the two aircraft are very close, the throughput cannot be infinite because of the limited emission spectrum. For now, we consider that the maximum throughput is 5 Mbps. Now, we can associate the length of the connection with the available throughput. And, as the throughput decrease with the distance, we only need the length of longest edge of the path to the ground station. This edge is the bottleneck of the connection between the aircraft and the ground station. Figure 7 shows the maximum available throughput we obtain for all the flights.

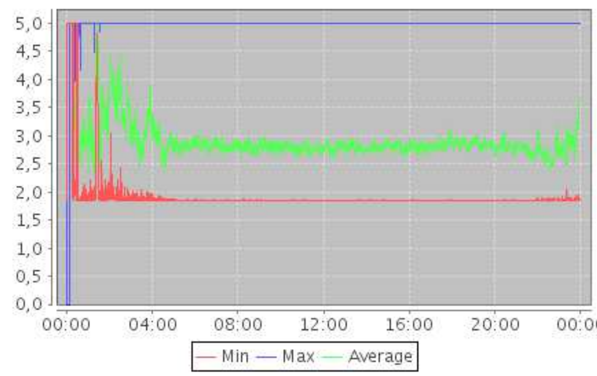

Figure 7. Maximum available throughput per aircraft

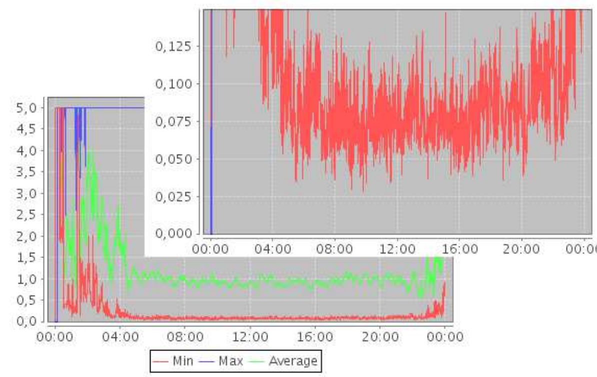

Figure 8. Fairly shared available throughput (Mbps) per aircraft

We notice that the minimum throughput for all the flights is about 2 Mbps. That is due to the fact that in this simulation, we have chosen a maximum range of 100 km for the aircraft and this distance gives a throughput of about 2 Mbps at 2 GHz.

B. Fairly shared available throughput per aircraft

In the first approach, only one aircraft sent messages. Of course, this situation is very unrealistic. We now consider that all aircraft can send messages, which implies that the available throughput of a link will be shared. We still consider that our routing protocol choose the shortest path to the closest ground station of the aircraft. Using the same method as in the first approach, the throughput/distance relation is calculated for a 2 GHz frequency. Finally, we consider that on each edge, the maximum throughput is fairly divided between all aircraft whose traffic uses this edge. Thus we can estimate the available throughput for each aircraft at each instant of our simulation. Figure 8 shows the average and the minimum throughput for all aircraft at each instant of the day.

We see that the average throughput is about 1 Mbps or more during the day. However, the standard deviation is high. That

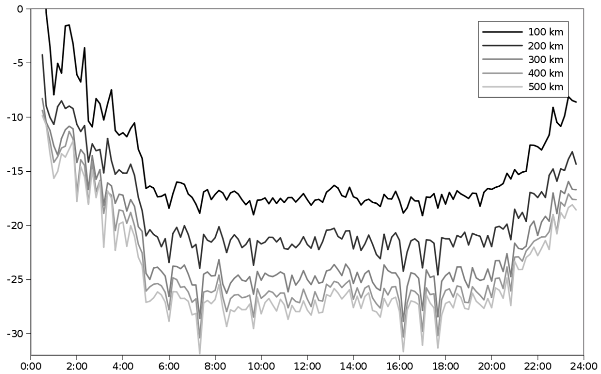

Figure 9. Average of the signal-to-noise ratio (dB) of all useful signals during a day for different ranges

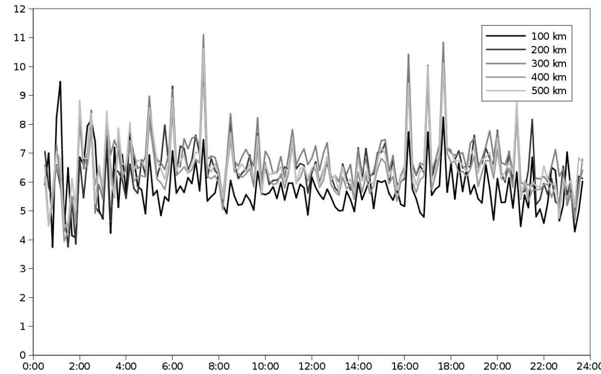

Figure 10. standard deviation of the signal-to-noise ratio of all useful signals during a day for different ranges

is probably due to the fact that we use the shortest path to the destination. This leads to a congestion around the ground stations. aircraft near the station have a higher throughput than those far from the station. In further study, the routing protocols will have to take this problem into account. We will probably have to use longer path to balance the load of the network on the different links.

C. *Interference estimation*

In the link budget presented in table \ref{tab:link_budget}, we have considered $\frac{E_b}{N_0} = 3dB$ to obtain a throughput of 100 kbps. We decided to check whether this level is reached or not.

1) Method: We have $(\frac{E_b}{N_0})_{dB} = G_e + (\frac{S}{N})_{dB}$, where $(\frac{E_b}{N_0})_{dB}$ is the energy per bit to noise power spectral density ratio, G_e is the processing gain and $(\frac{S}{N})_{dB}$ the signal-to-noise ratio. To make sure that we have a good $\frac{E_b}{N_0}$ ratio, we have compute the $(\frac{S}{N})_{dB}$ ratio of each connection in the network.

We consider here the worst case : each aircraft send data constantly. We consider that each aircraft is connected to the closest ground station by the shortest path given by the Dijsktra algorithm. We then consider that each aircraft has an emission power of 1W. In fact this value does not matter because what we want here is the signal-to-noise ratio of each connection, ie the ratio between the power of the given signal and the power of noise and other interfering signals. We do not consider here any control power algorithm : all the aircraft have the same emission power and they always use the same power, whether the destination is near or far.

Finally, we compute for each aircraft the SNR of each useful signal, considering that the power of each signals decrease in $\frac{1}{d^2}$ with the distance.

2) Results: Figure 9 shows the average of the signal-to-noise ratio of all useful signals during a day, considering different ranges for aircraft.

Figure 10 shows the standard deviation of the signal-to-noise ratio of all useful signals during a day for different ranges.

Figure 11 shows the minimum of the signal-to-noise ratio of all useful signals during a day for a range of 100 km.

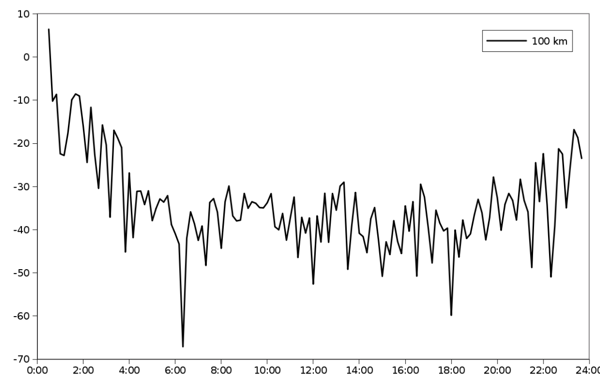

Figure 11. Minimum of the signal-to-noise ratio of all useful signals during a day for a range of 100 km

We can see that the shortest the maximum range is, the better is the signal-to-noise ratio and the standard deviation. It means that if we want to reduce the interference level in our system, we have to use short connections between aircraft. But as we can see in figure 5, if the maximum range of each aircraft decrease, the percentage of connected aircraft in the network decrease too. Thus the optimal range is about 100 km. For this range, the signal-to-noise ratio is about -17 dB on average, with a standard deviation of about 5 dB, but the minimum is about -40 dB. To design our system, we have to choose a maximum signal-to-noise ratio. We have chosen -25 dB. Indeed, with a signal-to-noise ratio of about -17 dB on average, with a standard deviation of 5 dB, this value allows us to guarantee the great majority of the connections.

3) Modification of the routing algorithm: As shown in figure 9, if we want to reduce the interference level in our system, we have to use short connections between aircraft. But we have chosen the Dijsktra algorithm to find the shortest path between each aircraft and the ground station. And as the shortest path between two points is the straight line, the Dijsktra algorithm will choose the direct line between two aircraft, even if there is another path between them with two shorter edges. That is why we decided to modify the weight of each edges so that the Dijsktra algorithm give priority to the shortest edges. The original weight of each edges was its length, it means the distance between the two aircraft. We

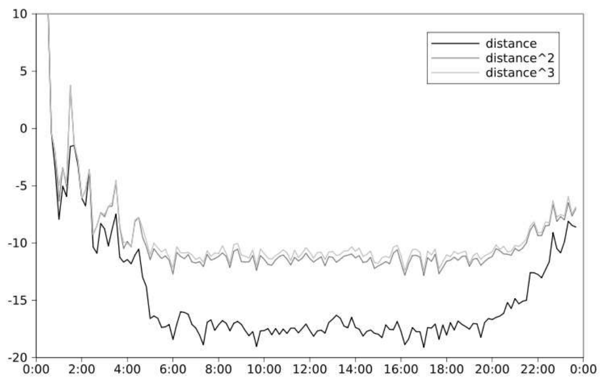

Figure 12. Average of the signal-to-noise ratio (dB) of all useful signals during a day for different edges weights

have made some tests with the distance to the power of two or three so that the longest edges are disadvantaged in the Dijsktra algorithm. Figure 12 shows the results.

We obtain an increase of about 6 dB on the average of the signal-to-noise ratio of all the useful connections. It means that we can decrease the interference level of our system by choosing a path that uses the shortest available connections to reach the destination.

V. Conclusion and Future Work

In this paper, we have considered a solution with an aeronautical ad hoc network to provide a new data-link to aircraft. The objective was to demonstrate the feasibility of such a network. We have shown that with a 100 km range, 96.50% of aircraft were connected between 6 a.m. and 9 p.m. Then, we have shown that, even with a simple routing protocol such as the shortest path, we offer a higher throughput to each aircraft than the throughput offered by existing solutions such as VDL Mode 2.

For our future works, we will have to study the routing algorithm in order to reduce the interference level of the system. Then, we will have to demonstrate the feasibility of our solution in other areas, for example in Europe, in the United States or in the North Atlantic corridor. Finally, we will study the performance of an aeronautical ad hoc network for other aeronautical communications, for example for In-Flight Entertainment (IFE). To provide higher throughput, we are working on an hybrid topology with an aeronautical ad hoc network as access network and a satellite link as return channel. Figure 13 shows this topology.

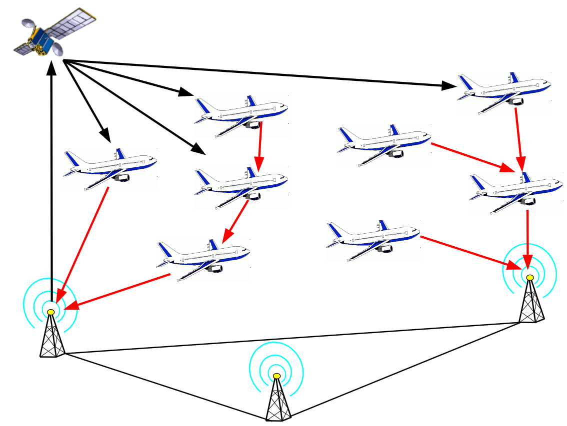

Figure 13. Hybrid topology

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