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Availability of Aeronautical Ad-hoc Network in Different Global Air Transport Fleet Scenarios

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Abstract

Internet connectivity is ubiquitous today and the desire for communication services doesn't halt before the aircraft cabin. The means to enable cabin connectivity include radio-based satellite and cellular access technologies, which are inherently limited concerning capacity, reach and delay. Aeronautical ad-hoc networks (AANETs) promise better capacity with enhanced reach compared to air-to-ground solutions, and lower infrastructure cost, better capacity and lower path delay compared to satellite. In this contribution, practical boundary conditions of AANETs are investigated using a global air traffic model. The expected node degree and the related reach, expressed by the ratio of connected aircraft, are regarded. Scenarios with and without satellites are considered.

1. Introduction

Aeronautical ad-hoc networking (AANET) may add additional bandwidth to commercial flights, potentially surpassing existing solutions by orders of magnitude. Free-space optics (FSO) is a prime candidate to provide high bandwidth to aircraft as nodes in partially connected mesh networks, without the need for spectrum allocation. Previous investigations of AANET have a focus on radio-frequency-based networks with reconfigurable antennas. Aspects such as connectivity, link dynamics, routing [1-4] and gateway selection [5] have been addressed with special regard of North Atlantic routes and European air traffic [6, 7]. Simulations which include steerable antenna modeling in AANETs over the continental USA have also been performed, using FAA flight path data under consideration of different fleets [8, 9].

In this paper, AANETs are modeled on a global scale. The focus is on topology aspects and the impact of adding satellite connections on network availability is evaluated, in terms of the achievable ratios of connected aircraft.

2. Methods

Air traffic is modeled assuming great circle routes to avoid modeling complexity. Thus, we achieve lower bound aircraft densities and conservative estimates. Flight schedules from the OAG 2014 database[1] and BADA [10] aircraft performance data are used to determine trajectories for each aircraft type, when available – otherwise, a comparable type concerning seat count and propulsion system is used. As an infrastructure scenario must be defined for internet access, an algorithm is used to place terrestrial internet gateways (IGWs) on a quasi-equidistant grid over landmass, with a chosen coverage of approximately 25% overland. In other words, a sparse cellular arrangement of IGW, e.g., ground stations or high altitude platform stations (HAPS), is used. Some IGWs were added manually over islands. Three satellites are assumed in geo-stationary orbit in global scenarios, while a single one is assumed in the North Atlantic scenario.

In order to evaluate relevant metrics, a network topology is built in the form of a graph. Adjacency matrices are used to define availability of connections, considering the communication range between nodes. Four available connections are assumed per aircraft and IGW, limited by the number of laser terminals (LTs), which also means that only four aircraft may connect to IGW per cell. An aircraft is considered connected whenever a multi-hop path to an IGW or satellite is available. Network links are formed locally, using neighbor tables stored by each node and cost functions which may consider, e.g., distance and relative velocity. This is technologically viable and efficient, not requiring central network management.

Terrestrial IGW selection is straightforward insofar as aircraft may connect whenever within range. The large footprint of satellites allows distributing of connections not only to maximize connectivity, but also to alleviate data traffic loads by tapping large clusters, and to improve network stability. The number of connections is limited by available satellite LTs (SLTs). In this contribution, the ratio of connected aircraft is maximized to quantify the achievable gains in connectivity. To this end, clusters without IGW access are connected sequentially in descending order of size. Atmospheric effects are neglected, but an impact is expected especially due to the susceptibility of FSO to aerosol and hydrosol extinction. Potential impacts may be compensated in part by path diversity in the network.

3. Results

October 29, 2014 was selected as a representative day [11] and all airlines are considered. Simulations were run with a temporal resolution of 20 minutes over the course of 24 hours. In the following discussions, air-to-air communication range and the number of available SLT are varied. The communication range between aircraft and IGWs (or cell size) is fixed to 250 km, resulting in a total

[1] OAG Aviation Worldwide Limited: OAG Schedules Data 2014. Luton.

number of 267 IGW worldwide or 1068 IGW-LTs. This overestimates the number of required IGWs, e.g., because air traffic routes and remote regions are not considered by the placement algorithm. Complete coverage can be achieved over land by supplying a sufficient IGW density. The coverage ratio is roughly independent of cell size, but both determine the overall number of available IGW-LTs.

Figure 1. Visualization of the simulated airborne network, assuming a communication range of 250 km.

3.1 Global Scenario – All Aircraft (60+ seats)

The first scenario includes all flights with at least 60 seats. In total, 56,371 flights are regarded, and the number of aircraft in flight is shown in Figure 2 as function of time. Flights over land and water are distinguished, with considerably more aircraft over land. The mean available capacity per aircraft would ideally approach the number of active IGW terminals multiplied by link capacity, divided by the number of aircraft (ca. 5,000). Assuming a per-aircraft capacity of one tenth of the link capacity would then require at least 500 IGW terminals worldwide. In the scenario, 2,024 airports and 228 IGW are active.

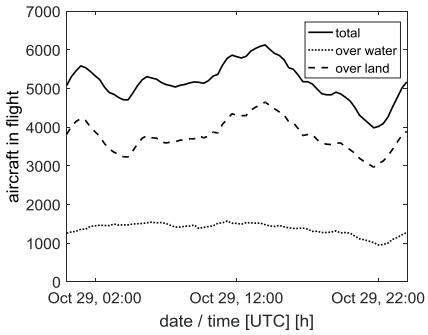

Figure 2. Number of flights in the global fleet scenario.

In Figure 3, the probability for different node degrees is shown. The node degree is the number of available connections per node, determined by evaluation of aircraft positions throughout the simulation run. A degree of two is required to form a linear chain, and a degree of at least three is required to form a mesh. With a range of 250 km, a degree of three can be expected with 85.9% probability.

In Figure 4, connectivity (here defined as the ratio of connected aircraft) is shown as function of available SLT. Curves are shown for different air-to-air communication ranges, which were varied between 150 and 450 km, differentiating between flights over land and over water. More flights are connected over land due to IGW vicinity.

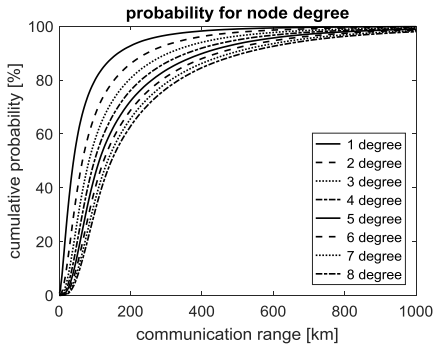

Figure 3. Statistical node degree between aircraft in global scenario.

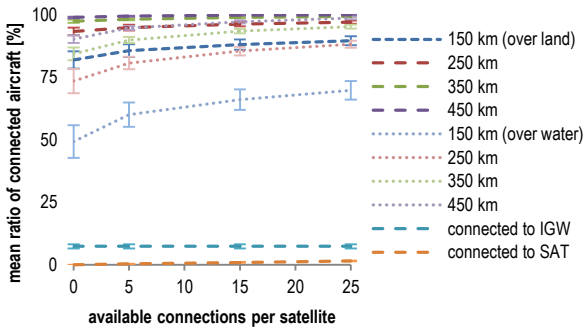

Figure 4. Mean ratio of connected aircraft in global scenario. Also shown is the share of aircraft connected to IGW and satellite. The error bars show the standard deviation in each simulation run.

Over land, a mean share of 81.8% of aircraft is connected even with a communication range of 150 km and without satellite connections, due to the large number of domestic flights. The relative share of connected oceanic flights is much lower when the communication range is small, and connectivity is chiefly limited to coastal areas. The benefit of the airborne network can be quantified: only 7.3% of all aircraft connect to ground directly, and this number remains constant on average. The share of aircraft using satellite connections increases linearly with the number of available connections up to 1.5% (~3x25/5000) – all other connected aircraft participate via ad-hoc networking. The gains in connectivity taper off toward higher range and higher numbers of satellite connections. Still, increases of both still may benefit the network. Higher communication range may increase network throughput and resilience by improved graph connectivity, and additional SLT and IGW terminals add overall capacity to the network.

3.1 Global Scenario – Wide-body Aircraft

The second scenario considers only flights of wide-body aircraft, which typically fly long-haul routes. The share of wide-bodies is relatively small and more intercontinental and oceanic flights are expected. This is shown in Figure

5 – the total number of aircraft in-flight make up for less than one third of the total number in-flight in the first scenario. Overall, 11,552 flights are simulated. The share of aircraft over water makes up slightly less than half (around 44% on average) of all active flights. 392 airports appear in the scenario, and 224 IGW are active.

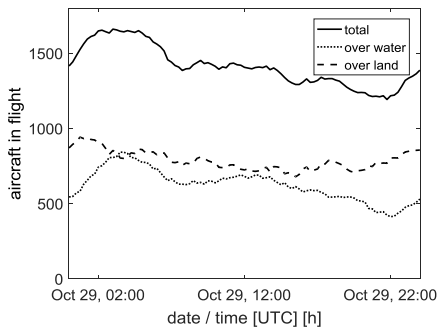

Figure 5. Number of flights in the wide-body scenario.

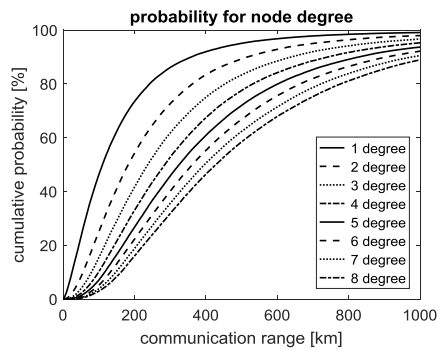

Figure 6. Expected node degree in wide-body scenario.

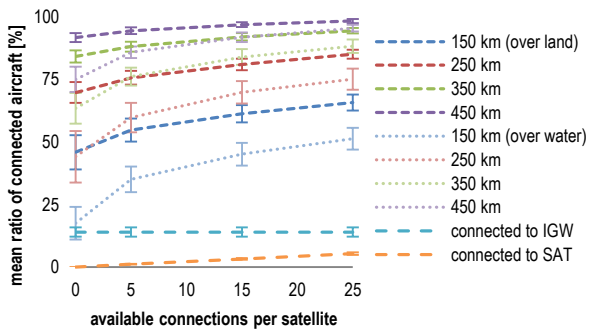

Figure 7. Ratio of connected aircraft in wide-body scenario.

The expected node degree is shown in Figure 6. Due to the reduced number of flights and the tendency of long-haul flights to disperse, with a 250-km communication range, a degree of three can be expected with only 52.6% probability. Again, the connectivity ratios are shown as function of air-to-air communication range (Figure 7). Due to the reduced number of flights, a larger share of 13.9% connects directly to IGW, and up to 5.3% to satellite. Increases in range and SLT number provide the highest gains at low range. The mean share of participating aircraft over water doubles by adding just 5 SLTs. The result shows that very high communication ranges are required to approach 100% connectivity.

3.2 North Atlantic Scenario

In the third scenario, only flights traversing the North Atlantic are considered by selecting flights between North America and EU, or the Middle East, according to OAG classification. The number of flights is shown in Figure 8. In this scenario, 83 airports and 43 IGW are active.

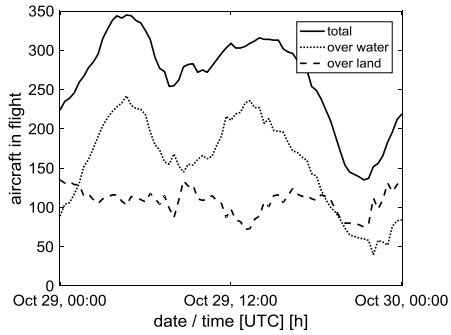

Figure 8. Number of flights in the North Atlantic scenario. A diurnal pattern due to east- and westbound flights is apparent.

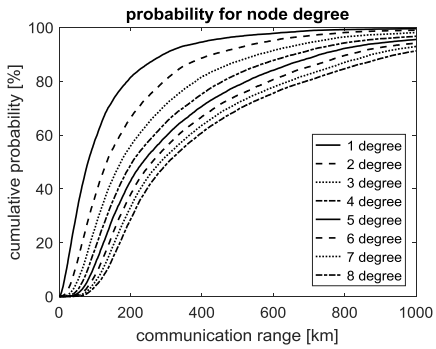

Figure 9. Statistical node degree in the North Atlantic scenario.

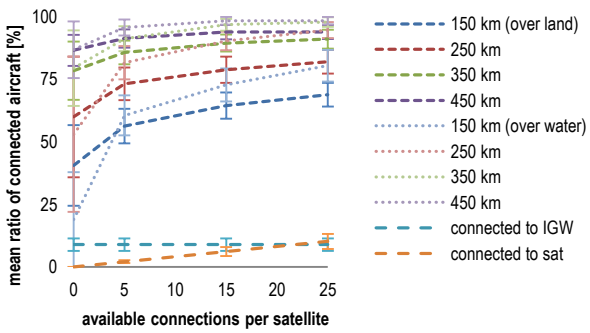

Figure 10. Ratio of connected aircraft in the North Atlantic scenario (connectivity tapers off at the highest communication ranges due to satellite coverage area).

The expected node degree (Figure 9), which depends on air traffic density, is slightly higher compared to the

global wide-body scenario. With a communication range of 250 km, a degree of three can be expected with 64.4% probability. Again, the mean connectivity (i.e., ratio of connected aircraft) is shown as function of air-to-air communication range in Figure 10. In this scenario, only 18.9% of flights over water participate on average, when communication range is 150 km. This figure increases to up to 86.8% at the highest considered communication range. Large gains are also achieved by adding SLTs – with just 5 SLTs, mean connectivity may triple. The share of connected aircraft over water then surpasses that of aircraft over land, due to the high share of oceanic flights and limited satellite availability in the scenario.

6. Conclusions

Free-space laser communication ranges of up to 150 km have been demonstrated in ground-to-ground and air-to-ground experiments [12, 13]. At typical cruise altitudes, favorable conditions can be assumed due to the lower air pressure and water vapor content. However, clouds in the transmission path statistically limit achievable distance and commercial laser terminals may trade performance with cost. Thus achievable air-to-air communication range may well be below 250 km. Under these considerations, it was shown in great-circle based simulations that node density is generally not sufficiently high to provide continuous connectivity to all flights via ad-hoc networking, with gateways available only overland. At 250-km range, between 56.7% (North Atlantic) and 87.9% (all flights >60 seats) of all aircraft may participate on average in the defined scenarios, mainly due to limited opportunity for access to aircraft over water.

Coverage can be improved by adding high-capacity relay satellites to connect remote clusters. As laser links are point-to-point by nature, the number of terminals per satellite is assumed to be limited. Assuming 25 terminals per satellite improves the figures mentioned to 88.5% and 94.5%, respectively. It is evident that the first satellite terminal provides the highest benefit, as it can be used to connect the largest disconnected cluster. The second terminal connects the second largest disconnected cluster and so forth, so that the benefit per terminal in terms of connected aircraft diminishes. The highest gains in terms of connectivity are provided at the lowest communication range, as clusters of aircraft are more likely to be disconnected. In regions with sparse air traffic and isolated aircraft however, high-speed links are not required, as these are best employed for adding capacity to clusters of aircraft. In this way, the laser-based ad-hoc airborne network can be seen as a complementary technology that provides additional capacity, freeing up radio bandwidth for other telecommunication systems.

6. Acknowledgements

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7. References

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