Scaling of Airborne Ad-hoc Network Metrics with Link Range and Satellite Connectivity

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Abstract: *In this contribution, large-scale commercial aeronautical ad-hoc networks are evaluated. The investigation is based on a simulation environment with input from 2016 flight schedule and aircraft performance databases for flight movement modelling, along with a defined infrastructure of ground gateways and communication satellites. A cluster-based algorithm is used to build the communication network topology between aircraft. Cloud top pressure data can be considered to estimate cloud height and evaluate the impact of link obscuration on network availability, assuming a free-space optics-based communication network. The effects of communication range, satellite availability, fleet equipage ratio and clouds are discussed. It is shown how network reach and performance can be enhanced by adding taps to the network in the form of high-speed satellite links. The effect of adding these is two-fold: firstly, network reach can be increased by connecting remote aircraft clusters. Secondly, larger clusters can effectively be split into smaller ones in order to increase performance especially with regard to hop count and available overall capacity. In a realistic scenario concerning communication range and with moderate numbers of high-speed satellite terminals, on average, 78% of all widebody aircraft can be reached. With clouds considered (assuming laser links), this number reduces by 10%.*

Key Words: *Aeronautical Ad-hoc Networks, Aeronautical Telecommunications, Laser Communication*

1. INTRODUCTION

Being always connected has become part of peoples’ lives. Ubiquitous broadband services have had a profound impact on everyday communication, and leisure activities involving audio, video, and games have found their way into mobile, connected devices. These trends do not halt before the aircraft cabin, and passengers today expect in-flight connectivity. As aircraft fly far, high and fast, traditional telecommunication solutions reach their limitations, with restricted range and bandwidth, and demand for radio spectrum. The main connectivity option is thus via satellite, with high infrastructure cost and long path delays. Air-to-ground solutions have also emerged, but these are chiefly limited to domestic flights.

Another concept involves aeronautical ad-hoc networks (AAHN), e.g. [1-3], where aircraft use multi-hop transmission to access satellite or ground gateways even beyond the radio horizon. High bandwidth and point-to-point capacities of many Gbit/s can be made available by free-space optical (FSO) laser-links [4,5]. In this way, the laser-based network complements other aeronautical radio solutions, potentially adding tremendous data exchange capacity to the air transport system. From a technological standpoint, it could integrate with existing infrastructure and offers future growth potential by successive addition of high-speed gateways. Opportunities may also arise from the mesh networking itself, even without instantaneous internet connectivity, by offering a larger set of up-to-date content to passengers by "crowd sourcing" of data, or by sharing of operations-relevant information such as weather data generated on-board. This could be promoted by using concepts from content delivery and information-centric networking [6], where data in the network is accessed by name instead of by address, enabling increased data availability irrespective of end-to-end connectivity, by means of data caching and replication methods.

In order to investigate the potentials and limitations of the concept of large-scale aeronautical ad-hoc networks, a simulation environment has been set up capable of modeling worldwide air traffic, based on the OAG (Official Airline Guide) flight schedule database. The physical layer of the network is built up according to a defined communication range and cost functions governing link formation. Cloud parameters can be considered in the simulation in order to estimate the impact on link availability. The impact of adding satellite laser links can also be assessed: These may improve connectivity and optimize network performance by better distribution of data traffic loads. Scenario-based evaluation of key parameters, such as overall connectivity ratios, effective cluster sizes, and temporal aspects, shows that network performance can be greatly enhanced with few satellite connections.

2. VARIABLES AND METRICS

In order to statistically evaluate the performance aspects of the airborne network, the following variables and metrics are defined. Specifically, with regard to the statistics, a differentiation between definitions of clusters is required to interpret the statistical results, as described in Table 1.

Table 1: Metrics for network evaluation

Variables	**Definition**	**Nomenclature**
Aircraft (AC) index	Aircraft index	i
Equipage [%]	Ratio of aircraft in flight with ad-hoc networking ability	eq
Air-to-air communication range	Maximum allowed range for aircraft-to-aircraft links	R_{AC}
Set of AC in-flight	Defined by timeframe between take-off (to) and landing (ldg)	$AC = \{i \mid (t_{\mathrm{to}}^{i} < t) \wedge (t_{\mathrm{ldg}}^{i} > t)\}$
Number of AC in-flight	-	$n_{\mathrm{AC}} = \lvert AC \rvert$
over water	Defined according to topography map (topo) at coordinates (ϕ, λ)	$n_{\mathrm{wtr}} = \Sigma_{\mathrm{i}}(\mathrm{topo}(\phi(i), \lambda(i)) \leq 0)$
over land	Defined according to topography at location	$n_{\mathrm{lnd}} = \Sigma_{\mathrm{i}}(\mathrm{topo}(\phi(i), \lambda(i)) > 0)$
above clouds	AC with altitude (h_i) above cloud top altitude (CTA)	$n_{\mathrm{acl}} = \Sigma_{i}(h_i > CTA(\phi(i), \lambda(i)))$
Metrics	**Definition**	**Nomenclature**
Number of connected AC	Sum of AC with direct or multi-hop gateway (IGW/SAT) access	$n^{con} = \Sigma_{i}(\text{hop count}(i \rightarrow \mathrm{GW}) < \infty)$
Ratio of connected AC [%]	Total number of connected AC / total number of AC in-flight	$r_{\mathrm{tot}} = \frac{n^{con}}{n_{\mathrm{AC}}}$

Cluster size	Number of AC assigned to a cluster head (i.e. aircraft)	n_{CL}
“Network” cluster size	Either single cluster or union of interconnected clusters	n_{NW}
“Gateway” cluster size	Number of AC assigned to a GW (determined by vicinity to the nearest gateway according to “shortest multi-hop path”)	n_{GW}
Normalized graph flow (per-aircraft throughput estimation) [Gbits/s]	Maximum flow f through the network, defined by the number of inputs and outputs (i.e. gateway connections and aircraft), normalized to network size	$c_{\mathrm{ave}} = \frac{f}{n_{\mathrm{NW}}}$

3. METHODS

The simulation environment is realized in MATLAB. Flight schedule data is loaded from the OAG database, 2016 edition [7], and aircraft performance data from the Base of Aircraft Database (BADA) [8]. A compilation of required airport data (geographic location, time zone, elevation) from various sources is used as input for the trajectory calculations. For the sake of generality, flight movements are modeled based on great circle routes. For simplicity and computational efficiency, altitude and velocity are separated. To this end, the cruise altitude is calculated for maximum theoretical efficiency according to flight distance. Throughout the ascent and descent phases, altitude is determined according to given climb and descent rates from BADA, while velocity is interpolated from ground to cruise altitude. Finally, velocity is normalized in order to meet scheduled times.

A certain deviation from real flight routes is expected, because flight routes, air traffic management, weather impact on routing etc. are disregarded. These effects are expected to be larger for short-haul flights because of the longer relative time spent in take-off and descent phases. As flight movements are based on a schedule database, deviations from actually conducted flights are also to be expected.

For the consideration of cloud impact, cloud top pressure data is imported into the simulation environment for the respective days from NASA AIRS project datasets [9]. Cloud top pressure (CTP) is converted directly into cloud top altitude (CTA) to generate a global cloud cover matrix in the simulation – this is only an estimate, firstly as spatial resolution is limited and secondly because cloud top pressure is measured indirectly from satellite temperature measurements and does not necessarily signify actual cloud occurrence. Other cloud parameters that may be used to refine the model, such as cloud cover fraction, are not currently considered.

For each day, only an incomplete, contiguous cloud top pressure matrix is available according to the satellite swath path; therefore the data is interpolated both in space and also in time, the former to fill holes in the spatial coverage, and the latter to prevent temporal jumps in the cloud data in-between days.

In order to build the AAHN topology, a cluster-based algorithm derived from MOBIC (mobility based metric for clustering) [10] is employed.

The algorithm enables network self-organization by using local neighbor tables, is computationally efficient, exploits all available connections and allows cost-based optimization of the network topology based on defined goals. For example, relative velocities and distances of aircraft are considered, as well as link history, to improve link lifetimes within network clusters. The communication ranges (inter-aircraft and aircraft-gateway) are preset as inputs to the simulation, and used to generate local adjacency matrices (or neighbor tables) for each aircraft at any instant in time.

The algorithm then builds aircraft network clusters by assigning initial roles to individual aircraft: an aircraft can be a cluster head, a gateway node with a connection to an internet gateway (IGW), a member node assigned to a cluster head, or an undecided node. Cluster heads are assigned initially according to a weight function that evaluates relative mobility and centrality.

In this way, aircraft with the largest expected dwell times within their respective neighborhoods are selected.

Still undecided nodes may then connect to existing clusters and become member nodes. Nodes already assigned to a cluster may also connect to members of other clusters, thereby becoming gateway nodes between clusters.

For internet connectivity, ground connections are formed based on vicinity to aircraft and according to terminal availability. In contrast, high-speed satellite connections can be assigned rather deliberately due to the large satellite footprint.

The assignment can be done such that the overall ratio of connected aircraft is maximized, or to improve network performance by equalizing the numbers of aircraft per gateway (in the former case, observed improvements in overall connectivity are typically small, so the latter method is used). Note that the clusters defined by cluster heads (n_{CL}) are different from the clusters in the “cluster size” statistics below (n_{GW}). For the statistics evaluated below, which are concerned with giving an indication of communication network performance, aircraft are assigned to gateways by vicinity; therefore the cluster assignment differs from the previous cluster definition. For the throughput statistics, even larger clusters are considered (n_{NW}), as the throughput is based on the total number of gateway connections available to AAHN.

4. SCENARIO DEFINITION

There is considerable variability in global air traffic. Therefore we previously selected October, 29th 2014 as a representative day with respect to the overall number of flights worldwide, determined by calculating the residual of the mean flights per day [11]. We retained the date with the 2016 dataset, and a 24 hour timeframe is simulated. Relevant flights departing on October, 28th or arriving on October 30th are also considered here. As temporal effects are not evaluated in this contribution, a coarse time resolution of 15 minutes was chosen, which is adequate for the statistics we generate. In 15 minutes, aircraft typically travel up to 250 km, which is of the order of the communication ranges considered. As short-haul flights chiefly service domestic and overland routes, flights of modern widebody aircraft were selected for the following analyses, with at least 180 seats and flying times of at least 120 minutes, i.e. a subset of the total number of flights. We consider the flight selection to be most relevant for airborne network simulations, because short-haul flight reside chiefly near landmass, and also in denser air traffic areas, so that high network coverage is more easily obtained for these flights.

The number of modeled aircraft in-flight as function of time is shown in Fig. 1, with a distinction between overland and oceanic flights as well as the number of flights above cloud top altitude. On average, 2037 aircraft are in the air, of which around 45.8% are above water, and 8.9% are below the cloud top altitude (in any case, these are disconnected when clouds are considered in the simulation).

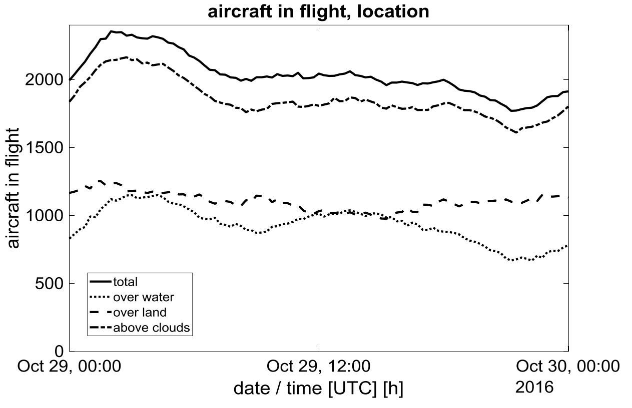

Fig. 1 – Number of considered aircraft in flight during the 24-h simulation run

Internet connectivity for long-haul aircraft is typically supplied by large geo-stationary communication satellites, and *Ku*- und *Ka*-band communication systems have enabled tremendous overall throughput per satellite on the order of 100s of Gbits/s[1]. Capacities to the end-user are much below this figure, however.

Ground-to-air networks for connectivity purposes are currently gaining traction as well, offering high-bandwidth communication in a cellular fashion, for example using LTE technology, e.g. [12]. Therefore, infrastructure for broadband aeronautical communication either exists, or is evolving in many countries.

The limitations of current infrastructure include long path delay in the case of GEO-satellites, while air-to-ground connectivity is unavailable to oceanic flights. Aeronautical ad-hoc networks can therefore leverage already existing infrastructure, firstly by increasing reach of air-to-ground connectivity via multi-hop communication, potentially improving mean packet delays and throughput compared to satellite, and secondly the utilization of available resources can be maximized by optimized distribution of requested data traffic, increasing the overall throughput of the existing infrastructure.

For the purpose of defining a future scenario for the airborne network simulation in this contribution, it is assumed that sparse air-to-ground connectivity is available globally over land, with a fixed communication range.

To this end, an algorithm places IGW on a roughly equidistant grid with approximately 25% overland coverage (i.e., the separation distance is approximately twice the distance required for full coverage). The communication footprint (IGW-to-AC) is fixed to 250 km communication range.

Also, the number of instantaneous connections per node (AC/IGW/SAT) is limited to a fixed number in the simulation, assuming that high-speed laser-terminals with Gbit/s point-to-point capacities will be used for AAHN in the future. In this contribution, it is assumed that four terminals are available on each aircraft and IGW, respectively. One consequence is that, even within an IGW cell, the number of ground connections is restricted.

Without loss of generality, IGW are assumed to be high-altitude stations placed 20 km above sea level, in order to avoid excessive link outages due to the cloud dataset.

As for satellite access, it is assumed that three GEO-stationary satellites are available, offering near-global coverage up to latitudes of about ±80° - the number of terminals is varied in this case.

[1] https://www.viasat.com/ViaSat-2-infographic-facts

5. RESULTS

The airborne network concept is based on the premise that a high node density is available with regard to communication range. Disregarding economic considerations, it still would take a certain amount of time to equip whole fleets of aircraft with ad-hoc networking ability. Therefore, in a first scenario we look at the mean ratio of connected aircraft, relative to the amount of equipped aircraft, as function of communication range. The result can be seen in Fig. 2. Here, the communication range was varied between 0 (no networking) and 750 km, and the percentage of equipped aircraft was varied between 10 and 100%. On the right, we can see the effects on the average cluster sizes (assigned to common gateway) in the simulation, and the upper and lower deviation from the mean. (The standard deviation in the ratio of connected aircraft is not shown, it is typically <5%.)

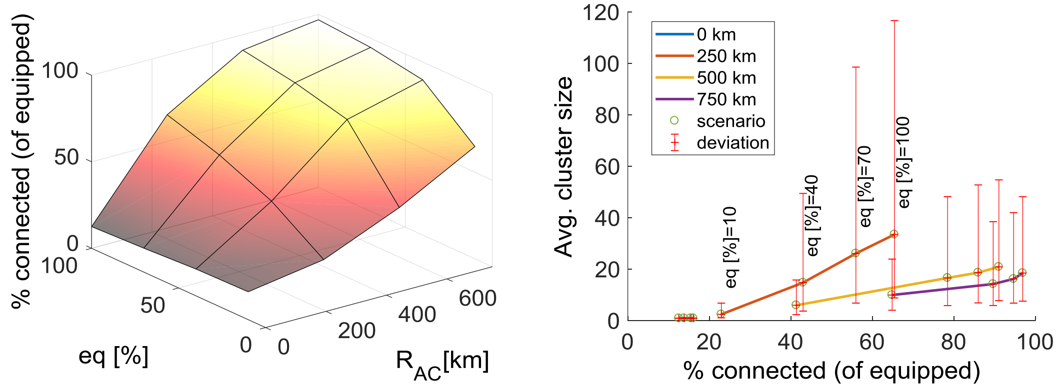

Fig. 2 – (Left) ratio of connected aircraft (with networking capability) vs. equipage ratio and air-to-air communication range. (Right) cluster size vs. ratio of connected aircraft (with networking capability). Equipage ratio increases towards the right-hand side. The deviation bars represent the variance of values above and below the mean for each 24-h simulation run

Both communication range and equipage rate are conducive to a high ratio of connected aircraft. Without ad-hoc networking (air-to-air range of 0 km) fewer than 20% of aircraft connect in the scenario (i.e., directly to ground stations). Connectivity peaks at 97%, with a high communication range of 750 km and full equipage of the considered fleet. The achievable communication range considering high-bandwidth solutions is expected to be much lower than 750 km, however. With a plausible range of 250 km, only about 60% of aircraft are connected on average, considering full equipage. Also, with 250-km range and a fully-equipped fleet, clusters become the largest with also a large variance, due to limited gateway availability. Between 250 and 500 km, the strongest performance improvements are obvious from the statistics.

The throughput per aircraft can be estimated according to graph theory, and the cumulated probability of achieving a mean throughput per aircraft is shown in Fig. 3. Mean throughput is calculated for each ("network") cluster according to the maximum flow considering the inputs and outputs (i.e. gateways, aircraft, and link capacities). In this case, a capacity of 1 Gbit/s was assumed for each link (aircraft-aircraft, aircraft-gateway and aircraft-satellite). For improved clarity, some data points were disregarded (no networking/ extremely long range/full equipage). Again, the improvements in connectivity with communication range and equipage ratio can be seen. The steepness of the curves shows that, as average network size increases with communication range, data rates saturate earlier (on average).

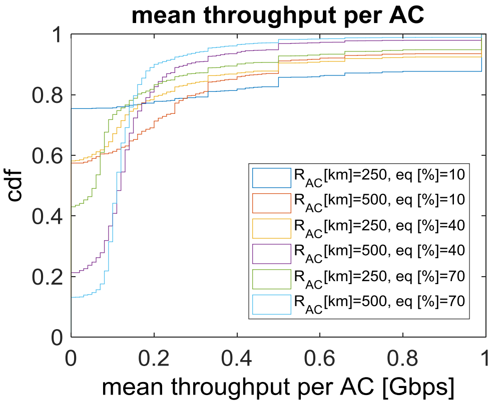

Fig. 3 – CDF of mean throughput per aircraft, calculated in the scenario described above. Some data points were left out for clarity

For the sake of brevity in data presentation, the impact of satellites on overall connectivity is discussed next with air-to-air communication range set to 250 km, which we consider viable in the near future with laser communication. The satellite algorithm optimizes for both connectivity and cluster size, and distributes its available satellite laser terminals (SLT) to aircraft accordingly.

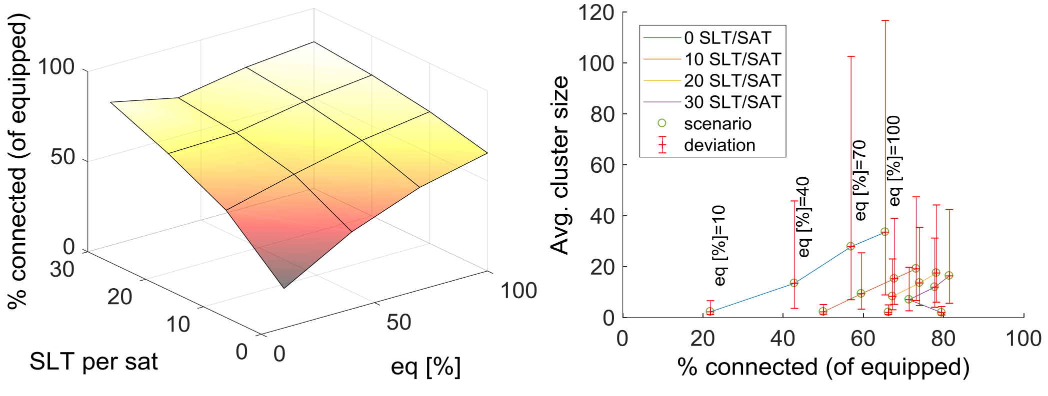

Fig. 4 – (Left) ratio of connected aircraft with networking capability vs. number of laser terminals per satellite and equipage ratio. (Right) cluster size statistics vs. ratio of connected aircraft with networking capability

By adding satellites, connectivity in the network can be drastically improved especially for small fleets with limited communication range, which can be seen in Fig. 4 (left) in comparison to Fig. 2 (left). When the fleet is very small, a high ratio of aircraft connect to satellite directly. With 250 km air-to-air communication range, without satellite about 66% of aircraft could connect to the network, assuming a fully equipped fleet. With SLT, this figure rises to around 80%. Cluster size statistics are improved as well, as both the mean size and the variance are reduced considerably.

In Fig. 5, the effect on throughput is shown. As a high ratio of aircraft connects to satellites directly or via small ad-hoc networks at a low equipage ratio, throughput per connected aircraft is higher. In the case of higher equipage ratio, there is a gradient towards higher throughput due to increasing node density and cluster sizes. Some jumps in the statistic are obvious and these can be explained by the fact that the mean throughput was calculated by dividing the (discretized) capacity per cluster through the (discretized) number of aircraft in that cluster.

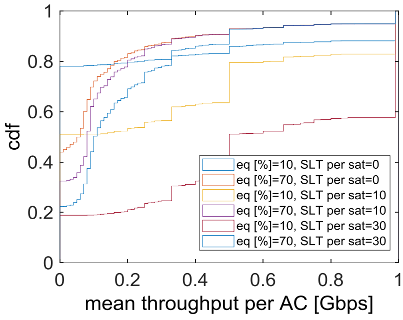

Fig. 5 – CDF of mean throughput per aircraft, calculated in the scenario described above. Some data points were left out for clarity

Cloud top data are considered next. In the previous calculations, there were no restrictions on connectivity besides communication range and terminal availability (also, aircraft could connect to the network from take-off until landing). With the added cloud top data, all connections between nodes with clouds within their line-of-sight path are disabled. Therefore, most aircraft lose their connections during ascent or descent phase, but also some horizontal connections between aircraft and neighboring nodes are lost. Again we plot statistics similar to those before; this time, air-to-air range was fixed to 250 km and a number of 20 SLT was chosen per satellite.

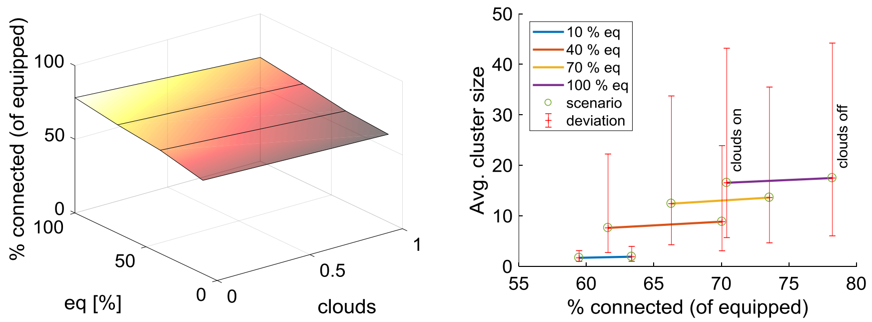

Fig. 6 – (Left) ratio of connected aircraft with networking capability vs. equipage ratio and cloud consideration. (Right) cluster size statistics vs. ratio of connected aircraft with networking capability

From Fig. 6, at 100% equipage ratio, connectivity is reduced by 10% (from 78.2% to 70.4%), in the given communication range and satellite infrastructure scenario. This compares to 8.9% of aircraft which are below the cloud top altitude, i.e. beyond those aircraft, there is only a small impact of clouds on overall connectivity in the simulation.

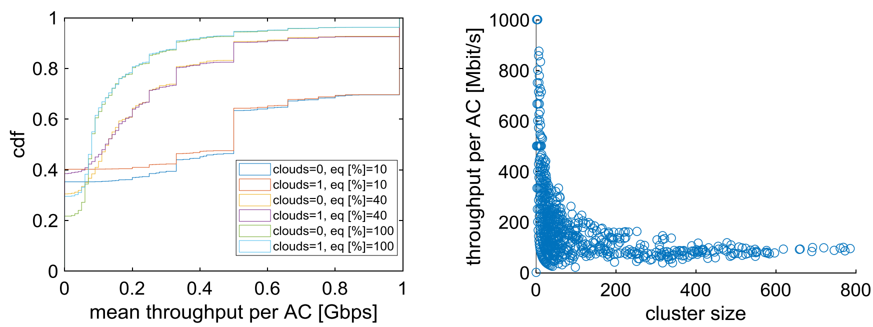

Fig. 7 – (Left) CDF of mean throughput per aircraft, calculated in the scenario described above. Some data points were left out for clarity. (Right) scatter plot of the mean throughput per aircraft with regard to cluster size

The mean throughput is shown in Fig. 7, and a slight change is seen. The impact of cloud obscuration is chiefly limited to the reduction of overall connectivity. Also, a scatter plot showing the throughput normalized to aircraft number with regard to cluster size is included ("network" cluster, size n_{NW}). Network sizes reach up to nearly 800 aircraft in this scenario, i.e. around 40% of all widebody aircraft worldwide could participate in a single, large network at times, with a communication range of 250 km.

5. SUMMARY AND CONCLUSIONS

In this contribution we have discussed the impact of communication range, satellite availability and cloud cover on the theoretical availability of airborne communication networks. Overall connectivity scales with air-to-air communication range, due to the fact that larger clusters may form at a given air traffic density. Also, with larger air-to-air range, aircraft may gain access to an increasing number of gateways. The ratio of gateways with regard to the number of networked aircraft determines the achievable, instantaneous internet throughput. It is reasonable to assume that this is where the bottleneck lies, as there are typically more aircraft per cluster than gateway connections (otherwise, the benefit of connectivity via airborne networking would also be diminished). Excess capacity in the network is therefore expected, and this may be used for non-internet, air-to-air data exchange. This can also be seen in the presented figures which show the average throughput per aircraft according to graph flow theory, which is mostly below the capacity of individual links, and never higher. Adding satellites is another means to increase both connectivity and network performance, by introducing additional gateways which can be assigned almost arbitrarily to aircraft, within the satellite footprint. Therefore, it is possible to drastically increase connectivity, by connecting the largest disconnected clusters first, and then using the remaining connections to tessellate large clusters into smaller ones to improve throughput.

The optimization of airborne ad-hoc networking scenarios depends on several boundary conditions, including the considered equipped fleet, communication ranges and capacities, gateway placement, and satellite availability. After an initial assessment of network availability as function of communication range, the communication range was thus fixed to 250 km as a credible range for laser communication systems. Unfortunately, in the scenario considering only long-range, wide body flights, this range produces moderate connectivity but with the largest cluster sizes and variances. Adding satellite links alleviates this issue, which illustrates the impact of gateway availability on network performance, and points toward optimization potentials.

With a 250-km range, 25% overland coverage of internet gateways (with four available connections each) and three geostationary satellites with 20 terminals each, about 78% of aircraft connect on average either via ground, satellite, or ad-hoc connectivity. This number is reduced by 10% when clouds are considered – this does not affect aircraft during cruise as much as aircraft in the ascent and descent flight phases, when connectivity is typically not available to passengers today. While it is assumed that only laser links are available, which do not penetrate clouds, a hybrid system using radio frequencies as a fallback solution could alleviate this issue. While full connectivity is not achieved under these rather moderate assumptions concerning technology and infrastructure, the network can in any case be considered as an additional means for aeronautical connectivity, freeing up spectrum of existing, radio-frequency communication systems including satellites. Moreover, it adds capacity for aircraft-to-aircraft communication, which may facilitate the implementation of novel and innovative data services and applications, as illustrated above. A throughput assessment was conducted based on graph flow theory to give an estimation of the achievable bitrates per aircraft. Here it was assumed that each link has 1 Gbits/s capacity, and typical performance per aircraft is of the order of 100 Mbits/s. Throughput per aircraft could, of course, be improved by increasing per-link capacity, and at least 10 Gbits/s are feasible today per channel. Wavelength multiplexing may even increase capacities to the Tbits/s-regime in the future. Moreover, the numbers of terminals (on aircraft/IGW/satellites) may have an impact on the achievable throughput.

The scenario didn't consider narrow-body and smaller aircraft. Many narrow-bodies also fly longer range missions and the frequency and amount of short-haul flights are considerably higher than widebody flights. Therefore, considering those flights in the simulations will have impact on the overall results.

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