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Geographic Load Share Routing in the Airborne Internet

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Contents

Kurzfassung

Internetzugang im ozeanischen Flug wird heute mittels satellitengestützter Kommunikationssysteme realisiert. Die vorliegende Arbeit befasst sich mit einer alternativen Technologie zur Gewährleistung von Konnektivität an Bord. Die Grundidee besteht darin, Datenpakete von einer Bodenstation an diejenigen Flugzeuge zu übertragen, die sich noch in Reichweite der Bodenstation befinden. Die Datenpakete werden dann von einem Flugzeug zum anderen zu dem jeweiligen Zielflugzeug übertragen, in welchem die Daten empfangen werden sollen. Entsprechendes gilt in umgekehrter Richtung für das drahtlose Übertragen von Datenpaketen aus einem Flugzeug an eine Bodenstation, die sich außerhalb der direkten Reichweite des Flugzeugs befindet. Positionsinformationen, die durch GPS oder andere satellitengestützte Navigationssysteme zur Verfügung gestellt werden, können für eine positionsbasierte Weiterleitung von Datenpaketen von einem Quellnetzwerkknoten zu einem Zielnetzwerkknoten verwendet werden. Der Dissertation liegt die Aufgabe zugrunde, ein verbessertes Verfahren zur Übertragung von Datenpaketen und zur Verteilung von Datenverkehrslast in einem solchen aeronautischen Mesh-Netz zu schaffen. Ziel ist es, das Datenverkehrsaufkommen derart auf die Bodenstationen (Internet Gateways) aufzuteilen, dass unnötige Datenauslastung bei einer Bodenstation vermieden wird, während andere Bodenstationen überschüssige Kapazitäten aufweisen. Dies wird durch ein zentralisiertes Bodenstationsübergabemanagement erzielt. Das Übergabeverfahren prüft in regelmäßigen Abständen, ob ein Flugzeug eine kürzere Auslastungsentfernung (Congestion Distance) zu einer Bodenstation erzielen kann, unter Berücksichtigung der derzeitigen geografischen Verteilung der mobilen Netzwerkknoten und der Auslastungssituation an sämtlichen Bodenstationen. Simulationsergebnisse mit transatlantischem Flugverkehr zeigen, wie dieses Verfahren es schafft, die gesamte verfügbare Kapazität fairerweise unter allen Nutzern zu verteilen.

Chapter 1

Introduction

Contents

1.1 Internet in the Sky

Mobile communications and internet access are increasingly becoming an essential part of people's lives in today's information society. In recent years, airlines have shown growing interest in offering cellular and internet connectivity in the passenger cabin, especially in long-haul flights, to complement their In-Flight Entertainment (IFE) services. Long-distance flights typically traverse oceanic and remote airspace, e.g., large bodies of water, deserts, polar regions, etc., where no communications infrastructure can be deployed on the ground. As a result, inflight connectivity is provided by contracting a satellite link service for the backhaul connection. A number of satellite-based inflight connectivity providers have emerged, including Connexion by Boeing (now defunct), OnAir, AeroMobile, and Panasonic Avionics Corporation. When flying in continental airspace, i.e., over landmasses, connectivity may also be provided directly using an air-to-ground (A2G) access network. This is the approach followed by A2G Internet Service Provider (ISP) AirCell with their Gogo Inflight Internet service. In 2006, AirCell obtained a slice of FCC spectrum for A2G communications and currently operates a cellular access network of more than one hundred ground stations, providing full coverage to domestic flights within the continental United States.

This thesis is centered around the vision of the Airborne Internet [1] [2], a new paradigm for inflight connectivity based on the concept of *mesh networking* [3]. As illustrated in Figs. 1.1 and 1.2, the idea is to extend the coverage of A2G access networks by introducing air-to-air (A2A) communication links. By allowing aircraft themselves to act as network routers, an airborne mesh network is formed in the sky. Instead of using a satellite backhaul, aircraft in oceanic or remote airspace can reach back to the Internet by using neighbor aircraft (i.e., those within their radio horizon) as a substitute for the satellite. Offshore inflight connectivity is thus achieved by establishing a multihop A2G backhaul path to the ground infrastructure on shore.

From the A2G ISP's perspective, airborne mesh networking effectively extends the geographic coverage of their network beyond line-of-sight into oceanic and remote airspace without having to deploy additional infrastructure or relying on a satellite provider. From an airline's perspective, avoiding the satellite link can result in significantly reduced communications costs, as an A2G communications provider will in general be less expensive than a satellite provider [4].

Another potential benefit of aeronautical mesh networking is reduced latency compared to geostationary satellite-based access, enabling delay-sensitive applications such as voice and video conferencing. With a geostationary satellite, there is

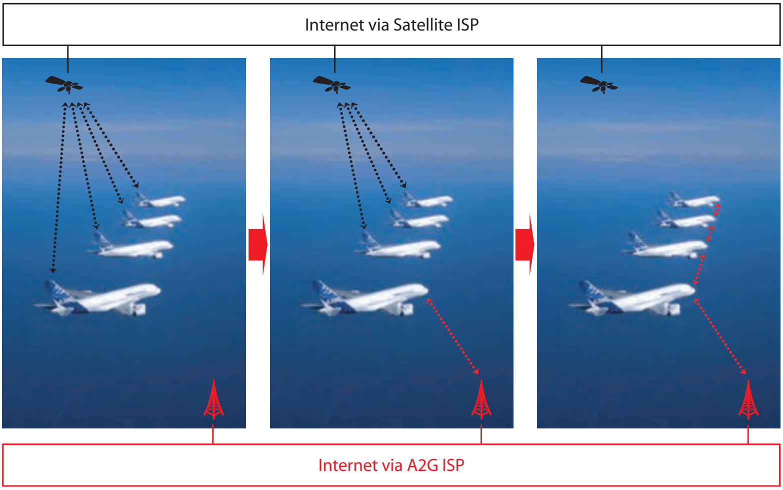


Figure 1.1. *Evolution from satellite-based to A2G inflight connectivity via airborne mesh networking.*

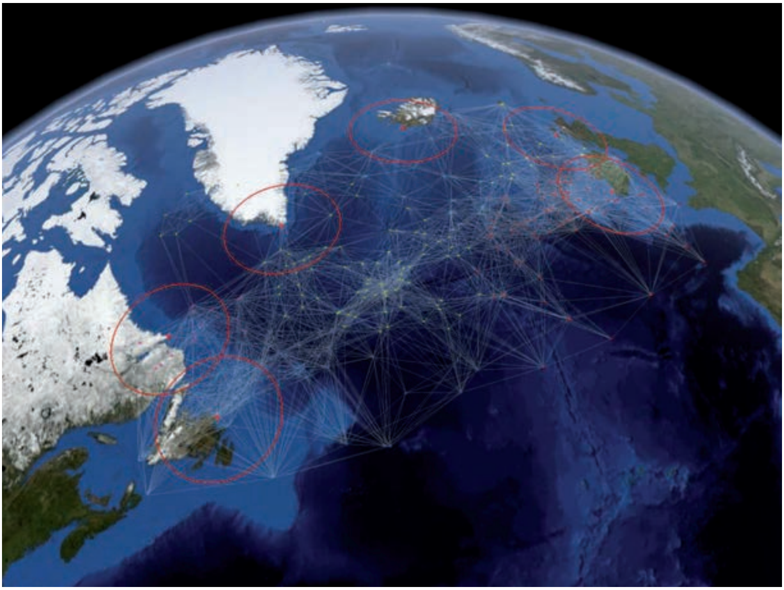
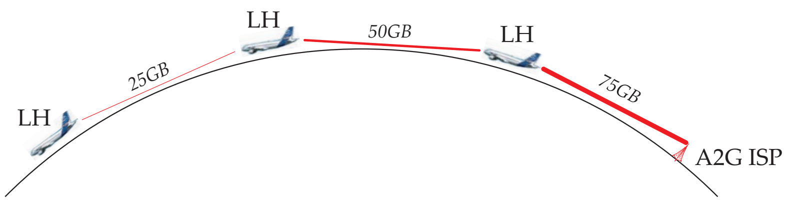
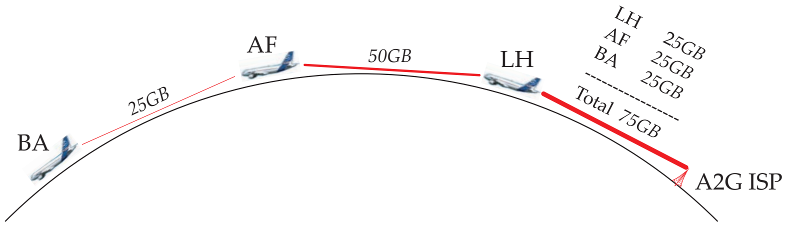


Figure 1.2. *The Airborne Internet (North Atlantic Corridor).*



(a) *Single airline*



(b) *Airline partnership among Lufthansa (LH), Air France (AF) and British Airways (BA)*

Figure 1.3. *Single-airline vs multi-airline airborne mesh networking.*

always a one-way end-to-end propagation delay of approximately 250 ms, required for the signal to travel up and down from the satellite. In the airborne mesh network, lower end-to-end delay guarantees can be provided by making use of appropriate Quality-of-Service (QoS) mechanisms, such as radio resource reservation or packet prioritization.

Finding a multihop A2G path may not always be possible for every aircraft, since air traffic density varies significantly both geographically and throughout the day. A satellite-based backhaul service could be used as a fallback solution, whenever the ground cannot be reached via a multihop A2G path. Whenever a path exists, however, the satellite link can be bypassed, allowing the airline to reduce its communication costs. A multi-link architecture similar to IEEE 802.21 Media Independent Handover (MIH) could be used to allow the aircraft to perform seamless handovers between the satellite, A2A and A2G interfaces.

As shown in Fig. 1.3a, a pioneering airline may initially rely only on its own aircraft for mesh networking, since it may be the only airline equipped with the required airborne technology (e.g., antenna, router, etc.). The spatiotemporal pattern of a typical airline's intercontinental (e.g., transoceanic) flight schedule is such that departures follow each other at a relatively constant rate for a few hours, giving rise to a string of aircraft heading toward the destination continent with a relatively con-

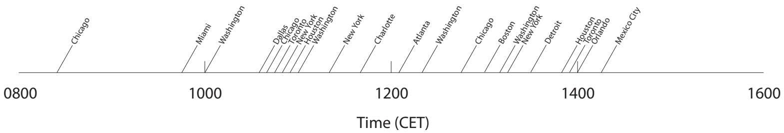


Figure 1.4. *Lufthansa's transatlantic departure schedule from Frankfurt airport (Summer 2010, source: http://www.frankfurt-airport.com).*

stant inter-aircraft separation. As an example, consider Lufthansa's current transatlantic schedule out of Frankfurt airport, shown in Fig. 1.4 (flights to the Western United States are not included, since they follow a northern route far from the main transatlantic axis). Between 0945 CET and 1415 CET every day, there is a scheduled Lufthansa departure bound for North America (out of Frankfurt airport alone) on average every 15 minutes. At a typical average speed of 900 km/h, this corresponds to an inter-aircraft separation of approximately 120 nmi (nautical miles). As we will discuss in detail in Chapter 2, the line-of-sight radio communication range between two aircraft is limited by the horizon (earth's curvature) and depends on the aircraft's flight level. At a typical cruising altitude of 35000 ft, A2A communication could be achieved in principle as far as 400 nmi. Also, note that the transatlantic gap between Ireland and Newfoundland (see Fig. 1.2) is approximately 1600 nmi wide, which corresponds to a flight time of 3.5 hours. As a result, the first flight reaches the North American coast before the last flight has even departed from Frankfurt, so that the mesh network is never disconnected from the ground. There is always a portion of the network flying over continental airspace, where A2G communications coverage is provided. Thus, a Lufthansa-only transatlantic airborne mesh network appears to be feasible. This is likely to hold for all major transatlantic carriers.

In the longer term, as more and more airlines equip for airborne mesh networking, *airline partnerships* may be formed to allow their aircraft to mesh together in a single unified cooperative network, as shown in Fig. 1.3b, building a more richly connected network. In this longer term vision, we can anticipate two possible business arrangements:

- A *split* ISP scenario, where the A2G ISP's communication service ends at the first hop (A2G link). Each airline in turn acts as a temporary "bridge ISP" itself for transit traffic to partner airlines downstream in oceanic airspace, and charges them, for example, according to the data volume transmitted on their behalf. An airline identifier could be included in each data packet to allow the airborne router to keep track of the data volume forwarded for each partner airline.

- Alternatively, a *transparent* airline scenario would be possible if the A2G ISP is willing to take responsibility for end-to-end multihop communication. In this case, the A2G ISP could charge each individual airline based on the aggregate data volume transmitted for its aircraft, regardless of which other partner airlines happen to act as a bridge to its ground infrastructure at any given time.

Another issue to consider is the lack of a frequency spectrum allocation for broadband A2A communications. One possibility would be to have a worldwide spectrum allocation for A2A non-safety-related communications (infotainment). Alternatively, the spectrum currently allocated to A2G inflight connectivity providers, such as AirCell, could be reused beyond the horizon for A2A communications, if the relevant regulatory constraints can be satisfied. For simplicity, throughout this thesis, we will assume that A2G and A2A communication links use the same carrier frequency.

1.2 The North Atlantic Corridor

Given the earth's continental geography and human demographics (responsible for the location of major airports and air routes), air traffic density is very heterogeneously distributed. Some regions, such as Europe and North America, experience a high density of air traffic, with aircraft headings being largely uncorrelated. Other regions, such as oceanic and remote airspace, are occupied much more sparsely, with aircraft typically flying along parallel routes. Moreover, the number of airborne aircraft in a given region changes significantly throughout the day, depending on the airlines' flight schedules. Of particular interest in this thesis are long haul transoceanic flight routes, which give rise to air traffic corridors between continents, resembling vehicle highways between large cities. The best example of these is the North Atlantic Corridor (NAC) between Europe and North America, shown in Fig. 1.5.

The North Atlantic is the busiest oceanic airspace in the world, and thus constitutes the best candidate scenario for a real deployment of an aeronautical mesh network. In 2007 approximately 425,000 flights crossed the North Atlantic [5]. As a result of passenger demand, time zone differences and airport noise restrictions, much of the North Atlantic air traffic contributes to two major alternating flows: a westbound flow departing Europe in the morning, and an eastbound flow departing North America in the evening. As shown in Fig. 1.6, the effect of these flows is to concentrate most of the traffic unidirectionally, with peak westbound traffic cross-

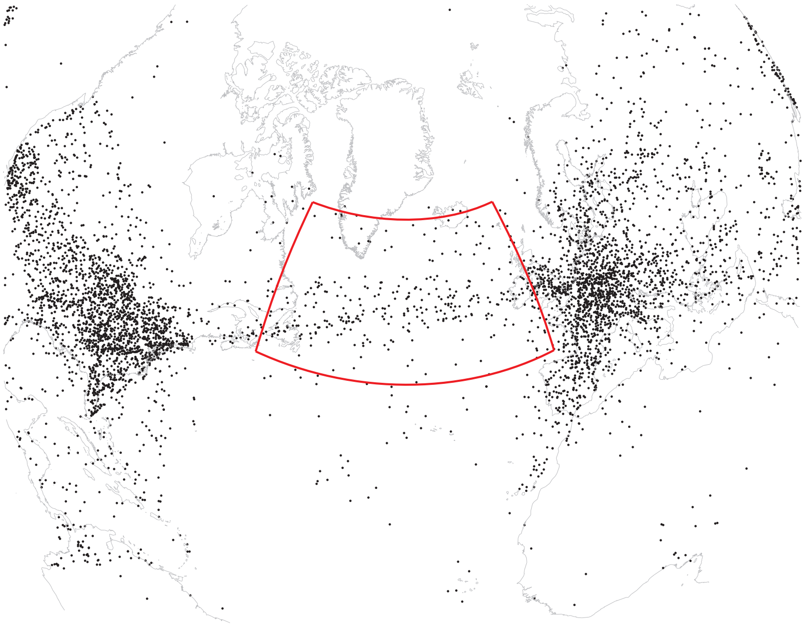
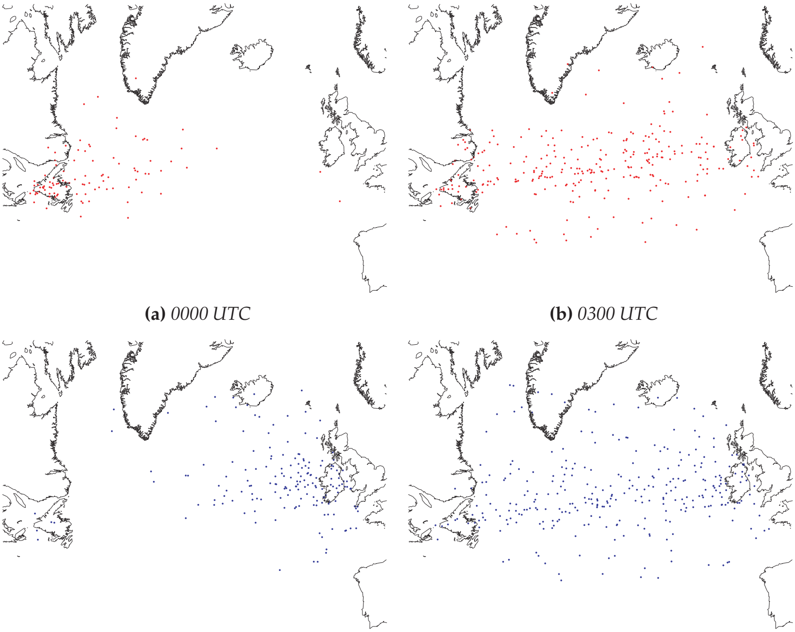


Figure 1.5. *Distribution of air traffic on the earth's surface at 1400 UTC, highlighting the North Atlantic Corridor. Flight trajectories are approximated by great circle arcs between departure and destination airports from the IATA airline schedule database.*

ing the 30W longitude between 1130 UTC and 1900 UTC and peak eastbound traffic crossing the 30W longitude between 0100 UTC and 0800 UTC.

For the purpose of this thesis, we define the North Atlantic Corridor as the lat-long rectangle from 45N to 65N latitude and from 5W to 60W longitude, as shown in Fig. 1.5. Fig. 1.7 shows the number of aircraft found within this area throughout the day. This curve changes slightly from one day to another, depending on the amount of transatlantic air traffic. The curve shown corresponds to an average day in 2007.

Due to the constraints of large horizontal separation criteria and a limited economical height band (FL310-400, or 9448-12192 m) the airspace is congested at peak hours. In order to provide the best service to the bulk of the traffic, a system of organized tracks is constructed to accommodate as many flights as possible within the major flows on or close to their minimum time tracks and altitude profiles. Due to the energetic nature of the North Atlantic weather patterns, including the pres-



(a) *0000 UTC* **(b)** *0300 UTC*

(c) *1000 UTC* **(d)** *1300 UTC*

Figure 1.6. *North Atlantic Corridor air traffic at different times during the day.*

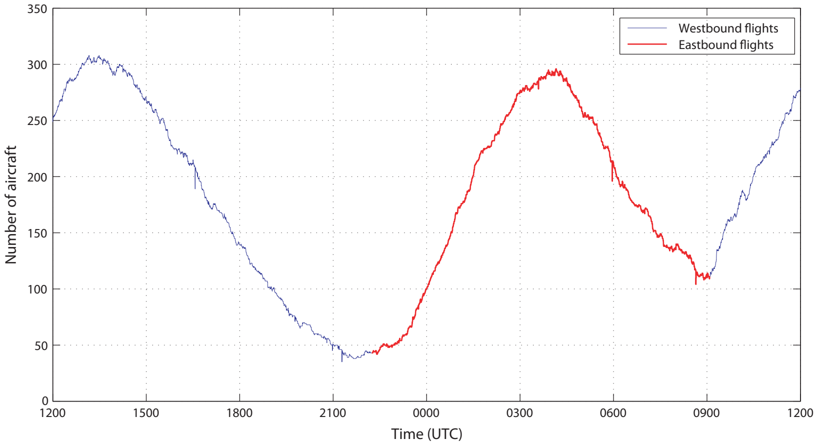


Figure 1.7. *Number of aircraft in the North Atlantic Corridor throughout the day.*

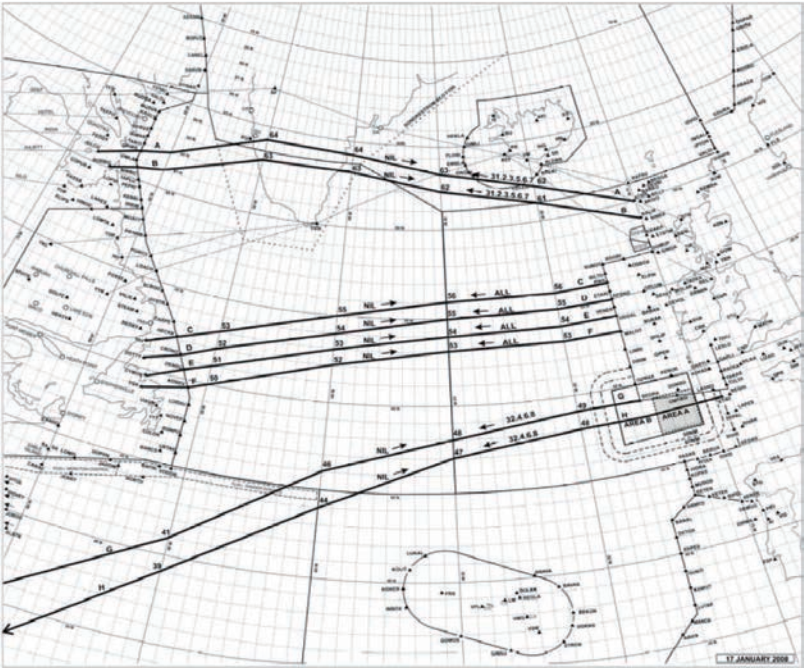


Figure 1.8. *Example of day-time westbound Organized Track System.*

ence of jet streams, consecutive eastbound and westbound minimum time tracks are seldom identical. The creation of a different organized track system is therefore necessary for each of the major flows. Separate organized track structures are published each day for eastbound and westbound flows. These track structures are referred to as the Organized Track System or OTS. An example of an Organized Track System is shown in Fig. 1.8.

1.3 Goal of this thesis

The Airborne Internet is characterized by a very special traffic matrix. All traffic flows from a set of geographically distributed ground stations (Internet Gateways) into the airborne mesh network (*downstream*) and from the airborne mesh network out to the Internet Gateways (*upstream*). As a result, every A2G link may pose a traffic bottleneck, since it must carry the traffic for all airborne nodes whose A2G path starts/ends with that link. This is shown in Fig. 1.9. In particular, note that

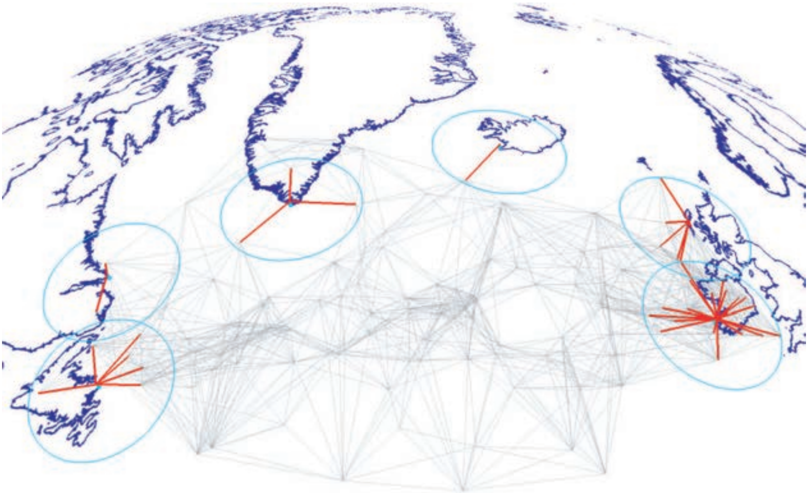


Figure 1.9. *A2G links (red) pose a capacity bottleneck in the Airborne Internet.*

given such a traffic matrix, the closer a link is to the access points, the more traffic demand it is likely to experience, as can be seen in Fig. 1.3b.

This thesis addresses the question: How can we route packets from the access network (formed by a set of geographically distributed Internet Gateways) to a given aircraft, and vice versa, from the aircraft to the access network, in such a way that we exploit the available capacity of *all* A2G links (shown in red in Fig. 1.9) connecting the airborne mesh network to the Internet? In other words, how can we share traffic load among all A2G links so as to avoid congestion at any particular A2G link while there is free capacity elsewhere in the A2G access network?

Generally speaking, the A2G path followed by a data packet, i.e., the sequence of intermediate nodes visited by the packet from the access network to its destination aircraft (or vice versa), has two degrees of freedom:

- On the one hand, there is in general more than one possible Internet Gateway from which the packet can be downloaded (or to which the packet can be uploaded). We will assume that all A2G traffic for a given aircraft is exchanged with that aircraft's default Internet Gateway, but which aircraft is assigned to which Internet Gateway will be a time-varying process. Topological and/or traffic dynamics may have an impact on which ground station acts as the aircraft's default Internet Gateway.

- On the other hand, there is in general more than one possible multihop path between the aircraft and its current default Internet Gateway, given the node density of the network topology. In particular, each of such paths may use a different A2G link as a first (or last) hop.

Thus, at any given time, an aircraft may be able to reach multiple Internet Gateways via a number of disjoint paths.

Routing plays an important role in avoiding congestion in multihop wireless networks, and therefore has a major impact on network throughput and packet delay. As an analogy, road congestion in a large city can be mitigated by rerouting cars away from roads that are close to saturation, if and when alternative routes to their destinations exist.

In so-called *multi-path* routing schemes (e.g., [6]), multiple paths are selected between source and destination. When a link is broken on a path due to bad channel quality or mobility, another path in the set of existing paths can be chosen. Thus, without waiting to set up a new routing path, the end-to-end delay, throughput, and fault tolerance can be improved, depending on the availability of node-disjoint routes between source and destination. A drawback of most existing multi-path routing schemes is their complexity and control overhead, since they must exchange topological information to find all available paths between source and destination. In a mobile environment, by the time this information has been collected, it may have become obsolete.

The main goal of this thesis is the design of a novel routing mechanism that exploits path diversity to reduce congestion at the bottleneck A2G links. Our proposed strategy takes advantage of the availability of GPS position information at each network node to perform opportunistic packet-by-packet geographic forwarding in the direction of the destination without having to exchange quickly changing topological information. In addition, buffer size information is used to balance traffic load both among next hop candidates in the direction of the destination and among Internet Gateways, in order to fully exploit the total A2G capacity available at any given time to the airborne network.

1.4 Related work

The concept of the Airborne Internet was first proposed at NASA Langley Research Center's Small Aircraft Transportation System (SATS) Planning Conference in 1999. In one conference session, it was suggested that such a system would require a peer-to-peer communciations network among the aircraft. The Airborne Internet Consortium (AIC) formed subsequently to promote and aid in the development of such a system. Consortium members include Aerosat, C3D Aero, and United Airlines. AeroSat, together with the U.S. Federal Aviation Administration (FAA), has performed flight trials with mechanically steered Ku-band antennas, demonstrating A2G link data rates of up to 45 Mbps over 150 nautical miles with a bit error rate (BER) of 5.10^{-5} [2].

A standardization effort known as DirecNet [7] has recently started in the United States. Nine major industry leaders have formed the DirecNet Task Force to develop an IP enabled, directional, high-bandwidth, ad hoc, highly mobile mesh network as an open validated industry standard. The proposed open-standard directional networking system is designed to provide a 1-gigabit-per-second data communication with anyone in a network on the ground, in the air or at sea, within hundreds of miles. DirecNet uses fast-steered directional antennas to substantially boost link power and operating range, and to permit reuse of radio frequency (RF) spectrum. Any DirecNet node can serve as a relay, multiplying connectivity and extending the range to beyond line of sight. DirecNet's standards are mainly directed at military communications systems for the battlespace (network centric warfare). However, this standard technology could be adapted for civil aviation use in the Airborne Internet in a very straightforward manner, given the clear similarities between both application scenarios.

Although a great number of routing protocols have been proposed for wireless mesh networks [3], none of them has been designed with the specific goal of aeronautical mesh networking in mind, and therefore they do not exploit the distinct characteristics of this environment. In the research community, only very recently has some attention been drawn to the application of multihop wireless networking to aviation [8]–[11]. However, these authors have a different focus other than broadband inflight connectivity provision.

In a preliminary work prior to this research [12], we presented a feasibility study of an aeronautical mesh network in the North Atlantic by using realistic air traffic from the International Air Transport Association (IATA) airline flight schedule database [13].

1.5 Outline of the thesis

The remainder of this thesis is structured as follows.

Chapter 2 discusses general properties we can expect to find in aeronautical mesh networks, such as a huge communication range and a fast topology change rate, which make this kind of networks somewhat different from traditional mesh networks. In addition, we provide an overview of key enabling technologies for broadband airborne mesh networking, such as smart antenas, time division multiple access, and geographic routing.

Chapter 3 introduces the core contribution of the thesis, Geographic Load Share Routing (GLSR). Given a specific network topology and traffic matrix (i.e., a set of traffic sources and destinations in a multihop wireless network), routing determines the traffic demand of each communication link. Whenever a link's traffic demand exceeds its capacity, congestion occurs. This is in particular of great relevance at the Internet Gateways, where each A2G link poses a potential traffic bottleneck and congestion is more likely to occur than elsewhere in the network. In order to mitigate congestion, GLSR exploits A2G path diversity by defining two novel metrics:

- The first metric, known as the *speed of advance* of a packet, combines the standard geographic routing technique (greedy forwarding) with a Join the Shortest Queue (JSQ) principle. This new metric takes into account not only the packet's advance toward its destination (as in greedy forwarding), but also the number of packets waiting for transmission in the corresponding buffer. By locally maximizing this metric, every router in the network spreads incoming traffic among all nodes in the direction of the destination, avoiding excessive queueing delay at its transmission buffers and eventually buffer overflow.

- The second metric, known as the *congestion distance* from an aircraft to an Internet Gateway, is used by the access network to control which nodes (aircraft) are assigned to which Internet Gateway based on the geographic coordinates of each node and the maximum average buffer size at the Internet Gateway. The goal is to compensate for spatiotemporal variations in traffic demand over the airborne mesh network by relocating nodes to less congested Internet Gateways whenever possible.

We provide a stochastic model of the speed of advance forwarding strategy, as well as a maximum throughput analysis of GLSR.

Chapter 4 presents our performance evaluation. We first describe in detail the Airborne Internet network model used in our computer-based simulations, including how we take into account directional transmission and multiple access interference. We use real airline flight schedules to generate air traffic in the North Atlantic Corridor and measure the throughput performance of GLSR compared to other simpler geographic routing schemes. Our results match the maximum throughput analysis given in Chapter 3 and demonstrate GLSR's ability to fully exploit the total A2G capacity available at any given time to the airborne mesh network. In addition, we demonstrate how our routing strategy reduces end-to-end packet delay by making opportunistic use of the path diversity in the mesh network.

Finally, Chapter 5 summarizes the contents of the thesis, draws the main conclusions of our work and discusses the outlook for the Airborne Internet.

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