

Two-Step Delay Based Internet Gateway Selection Scheme for Aeronautical Ad Hoc Networks

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Abstract—Recently, ad hoc networks have been proposed as a means of providing Internet access to passengers on board aircraft flying in oceanic or remote regions. The vast majority of data in such networks is either destined for or originated at an Internet gateway, which connects the ad hoc network to the Internet. Therefore, the allocation of aircraft to gateways plays an important role for the overall network performance. In this paper, we propose a new scheme for gateway selection based on estimation of the path delay, and demonstrate that this approach is indeed superior to common solutions based on hop count or gateway utilization in terms of packet loss ratio and mean delay.

I. INTRODUCTION

In the future, the demand by airline passengers for in-flight Internet services such as web browsing, e-mail, or Voice over IP will continue to grow. For purposes of air traffic control, a network of ground stations provides communication services in continental airspace. Obviously, such terrestrial base stations cannot provide coverage in remote or oceanic regions. Therefore, the common approach to provide Internet access for passengers has been via geostationary satellites, of which three are already sufficient to provide nearly global coverage. However, this approach has important drawbacks. The propagation delay of a signal from the aircraft to the geostationary satellite and back to a ground station is around 250 ms, which may cause problems for delay sensitive applications. Also, satellites are generally expensive to use, and require significant investments in aircraft equipment. To avoid these shortcomings, it has recently been proposed to form an ad hoc network between aircraft, allowing the coverage of air/ground base stations to be extended over multiple hops to aircraft in remote or oceanic areas [2], [3]. Aircraft that are equipped with a satellite link may also participate in this ad hoc network and may share their satellite link with other aircraft. The terrestrial ground stations or the aircraft with a satellite link connect the ad hoc network to the Internet and are referred to as *Internet gateways*.

A potential deployment scenario for an aeronautical ad hoc network over the North Atlantic is shown in Fig. 1. This image has been created from a database of real scheduled flights,

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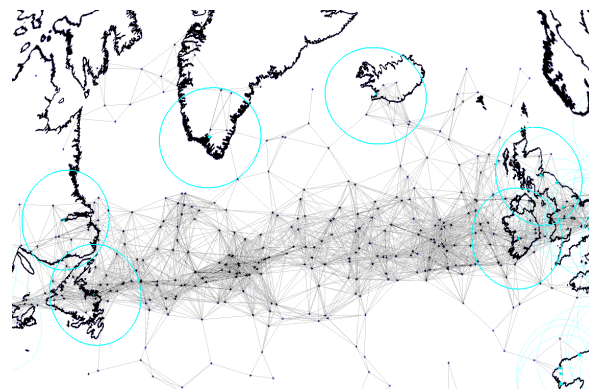


Fig. 1. Example for a potential ad hoc network over the North Atlantic

assuming Great Circle Routes and a maximum transmission range of 370 km. It can be seen that the network is well connected to gateways on both sides of the Atlantic, but gateways in Iceland or Greenland only provide limited additional connectivity. In previous work, we have characterized the connectivity and topology of potential aeronautical ad hoc networks based on real flight data for transatlantic flights in [4] and for European air traffic in [5]. The air to air links are characterized by a strong line of sight component and relatively high Signal to Noise Ratio, since the transmit power is not limited by battery constraints. Ultimately, the range is limited by the radio horizon.

Since we are interested in aeronautical ad hoc networks especially in remote or oceanic regions, the freedom regarding the placement of gateways is very limited. This is in contrast to typical Wireless Mesh Networks, which also aim to extend the range of fixed gateways via multiple hops, but where the placement of Internet gateways can often be optimized in advance.

The areas around the gateways are more likely to experience congestion than other parts of the network. Whenever more than one gateway is present in the network, the allocation of aircraft to gateways must be performed with care, in order to ensure efficient utilization of the network resources and balance the traffic such that congestion is avoided. Due to the limited flexibility regarding the placement of our gateways,

this problem becomes even more important.

The application of ad hoc networks to civil aviation has received relatively little attention so far. General issues regarding system design and network architecture have been addressed by Karras et al. in [2]. Sakhaee and Jamalipour [3] define a network architecture that attempts to minimize the traffic transmitted over either air/ground or satellite links in order to avoid the high cost associated with those links. For this purpose, Internet content is cached onboard each aircraft. When a user wishes to access a certain resource, it is only retrieved from the ground if an up to date version cannot be retrieved from any nearby aircraft. Both the caching of web content as well as the improvement of Internet gateway selection are complementary steps towards providing the quality of service that passengers will expect.

The rest of this paper is structured as follows: In Section II, we discuss the network architecture of an aeronautical ad hoc network. In Section III, we present the problem of Internet gateway selection and discuss several approaches that have been proposed so far. Then, we introduce our gateway selection scheme based on a two step approach and considering the delay of packets in the network in Section IV. In Section V, we define the link model used for our simulations. Finally, we present simulation results in Section VI and summarize our conclusions in Section VII.

II. NETWORK ARCHITECTURE

An aircraft can be seen as a mobile network. A number of hosts, i.e. passengers' laptops or phones, or other onboard devices, are connected to a mobile router onboard the aircraft. Since our goal is to provide IP based Internet services to the passengers, it is necessary that globally valid IP prefixes and addresses are assigned to the mobile routers and hosts, respectively. Autoconfiguration of IP addresses within an ad hoc network is addressed by the IETF Autoconf Working Group [6], but no solution has been standardized so far. This problem can be simplified by forming the ad hoc network at Layer 2, not at the IP layer. In this case, IP packets are tunneled through the ad hoc network, such that each aircraft is only one IP hop away from the access router on the ground, and standard IP mobility solutions such as the Network Mobility (NEMO) Basic Support protocol [7] can be used to configure valid IP prefixes for the mobile router on board the aircraft. The protocol architecture that we assume is shown in Fig. 2. The aircraft at the left side comprises a mobile host and a mobile router. The mobile router is running NEMO to ensure seamless global IP reachability, as well as the routing protocol of the ad hoc network underneath IP. Relaying aircraft, such as the one shown in the middle of Fig. 2, perform no IP processing, as the packets are forwarded at Layer 2. The gateway also runs the ad hoc network routing protocol, decapsulates the IP packets received from the ad hoc network and forwards them into the Internet.

This is similar to the approach that has been adopted by the Car2Car Communications Consortium [8], which considers

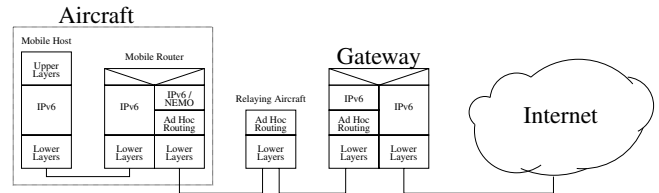


Fig. 2. Protocol architecture of the considered aeronautical ad hoc network

ad hoc communication between vehicles and access points installed along the roadside.

In principle, the decision, which aircraft uses which gateway, can be made either by the gateways or by the aircraft. The common approach, which we also follow here, is to leave this decision to the mobile node. Before selecting an Internet gateway, an aircraft must first become aware of the gateways that it can reach over the network. This process of Internet gateway discovery can be performed either proactively, meaning that the gateway periodically floods the network with gateway advertisements, or reactively, meaning that a node wishing to establish a connection with a host in the Internet floods a gateway solicitation through the network, to which all gateways respond with a gateway advertisement. In addition, hybrid approaches have also been proposed, e.g. in [9], in which the proactive flooding of advertisements is limited to a certain region around the gateway in order to reduce the overhead incurred by the periodic flooding. Nodes outside this region must discover a gateway reactively.

Reactive gateway discovery leads to an overhead that scales according to the number of nodes requiring a connection to the Internet, whereas the overhead of the proactive approach is independent of the number of active nodes. In case there are many nodes with a connection to the Internet, the overhead of the reactive approach has been shown to be higher than for the proactive approach [10]. Due to the aggregation of many passengers' flows at a single aircraft, it is likely that each aircraft will need permanent availability of an Internet gateway. For this reason, we assume proactive Internet gateway discovery. In the following section, we summarize several approaches to gateway selection, all of which are based on proactive discovery.

III. INTERNET GATEWAY SELECTION

The quality of an Internet connection is commonly characterized by the parameters packet delivery ratio (PDR) and mean packet delay, as they have a direct influence on the TCP throughput. We are only interested in these parameters for the wireless part of the network.

The most common method of Internet gateway selection is for every mobile node to choose the gateway that is closest in terms of hops [11]. Since neither the traffic load at the gateways, the gateways' capabilities, nor the amount of traffic in the MANET between the mobile node and the gateway is considered, congestion may occur in some parts of the

network, leading to excessive delay or even packet loss, whereas other regions may still be underutilized.

In contrast to this approach, Huang et al. [12] propose a gateway selection scheme that is based on the utilization of the gateways, i.e. the ratio of the amount of traffic handled by a gateway to the capacity of its wireless interface. The goal here is to balance the utilization of the gateways as much as possible. Each gateway keeps track of the traffic that it has handled during the last T seconds and advertises its current utilization to the nodes in the network, calculated as

$$L_i = \frac{\sum_x \rho_{x,i} \times T_x}{C_i}, \quad (1)$$

where C_i is the capacity of gateway i in bits per second, and $\rho_{x,i}$ is the fraction of its total traffic T_x that node x sends to gateway i . However, the distance between a mobile node and a gateway is not taken into account here, potentially leading to unnecessarily long paths through the network, and therefore also higher packet delay.

In [13], Brännström et al. have proposed to measure the variance in the delay between successive GWADVs and use this as the metric for gateway selection. Both a higher number of hops between the mobile node and the gateway, and a higher amount of traffic along the path will lead to an increase in the variance of the arrival rate of the advertisements.

Although delay is an important performance metric for interactive services, none of the solutions proposed so far directly considers the packet delay as a criterion for gateway selection. Therefore, a gateway with an air/ground link and a gateway with a satellite link will always be treated the same, even though the latter has a significantly higher delay. We conjecture that the gateway selection procedure can be improved by estimating the delay of packets in the wireless part of the network and using this delay estimate as a selection criterion. In the following section, we describe our new gateway selection algorithm based on the packet delay. Then, the performance of this new approach in terms of PDR and packet delay is compared to the hop count and the utilization based approaches by means of simulations.

IV. DELAY BASED INTERNET GATEWAY SELECTION

The delay that is experienced by a user is a depends on the traffic along the path in the network, as well as the traffic load of the gateway itself. By considering not only the delay of the packets within the ad hoc network, but also the large delay that is caused by satellite access links, we aim to shift traffic away from the satellite links as long as possible, i.e. when the overall traffic load in the network is sufficiently low. Only when the traffic begins to increase, leading to longer delay due to congestion around the terrestrial gateways, should more traffic be allocated to the opportunistic gateways.

Since the packet delay between the aircraft and the gateway is not known a priori, it must be estimated. One possible way to obtain this knowledge is to put a timestamp on the gateway advertisements. Specifically, we propose the following algorithm: The gateway advertisements flooded through the

wireless network carry a timestamp indicating when they were generated. If the gateway is an aircraft advertising its satellite link to other aircraft, the timestamp is set to the current time minus the propagation delay of the satellite link. Whenever node i receives a new advertisement with sequence number n from gateway j , it updates its corresponding delay estimate $d_{i,j}$ for the path between itself and gateway j according to the exponential weighted moving average

$$d_{i,j}(n) = (1 - \alpha)d_{i,j}(n - 1) + \alpha\tau_{i,j}(n), \quad (2)$$

where $\tau_{i,j}(n)$ is the measured delay of the n -th advertisement, and $\alpha \in (0, 1]$ is a parameter that determines how much weight is given to the new sample. The value for α should be chosen according to the rate of change of the network topology, which is influenced mainly by the relative speed of the mobile nodes.

Each mobile node shall rank all gateways from which it has received an advertisement according to their associated hop count h_i . Then, a reduced set of candidate gateways \mathcal{H}_c is determined, such that

$$\mathcal{H}_c = \{i | h_i - \min_j \{h_j\} \leq \delta_h\}, \quad (3)$$

where δ_h is a threshold that determines how large the difference in the hop distance to the closest gateway and any other potential gateway may be. From this reduced set \mathcal{H}_c , a node selects the gateway with the lowest associated delay estimate. Effectively, the threshold δ_h creates regions of hosts that are associated with a certain gateway since they are sufficiently close to that gateway, as well as a transient region of nodes that are similarly close to two or more gateways and where the decision is based on the delay. The benefit of considering only the closest gateways is that the hop count is a very robust metric that does not depend on any dynamic estimates.

In a second step, we sort the gateways in the candidate set \mathcal{H}_c by their delay estimate calculated from the received advertisements according to Eqn. 2. If the node's current gateway is the one with the lowest delay, the node keeps this gateway. If a different gateway has a lower delay estimate, the node begins to split its traffic between this gateway and its current gateway for a short duration T_{split} and measures the delay that is experienced by the data packets sent to each gateway.

The reason for this is that the delay estimate based on the advertisements may not reflect the delay of the data packets, either due to the broadcast nature of advertisements, their smaller size, or possibly different levels of priority. After T_{split} , the node selects the gateway with the lower delay for data traffic. In order to prevent mobile nodes from switching back and forth between gateways frequently, we require that a node stays with a gateway for at least T_{hold} seconds. Only if a node has been using its current gateway for longer than T_{hold} seconds does it invoke the gateway selection procedure described above, which is triggered by the reception of a new gateway advertisement. This gateway selection algorithm is summarized in Alg. 1.

To reduce the overhead due to the flooding of advertisements, each node only forwards gateway advertisements for

Algorithm 1 Delay Based Gateway Selection Algorithm

```
if current GW used less than  $T_{\text{hold}}$  s then
  keep current GW
  return
else
  determine subset of candidate GWs  $\mathcal{H}_c$  acc. to Eq. 3
  if current GW has lowest delay of all GWs in  $\mathcal{H}_c$  then
    keep current GW
    return
  else
    begin splitting traffic between the two GWs in  $\mathcal{H}_c$  with
    the lowest delay estimate from GWADVs;
    measure the delay of the data packets sent by each GW
    wait  $T_{\text{split}}$  s
    select the GW with lower delay of data packets as
    default GW
  end if
end if
```

the gateway which it has selected. This has no effect on the gateway selection process, since both hop count and delay strictly increase each time the advertisement is forwarded.

V. LINK MODEL

The vast majority of all simulations in the field of wireless ad hoc networking is performed using IEEE 802.11 as the underlying link technology. However, our work is motivated by the use of ad hoc networks for multihop communications between aircraft, and it is highly unlikely that WiFi will be applied to this setting. Therefore, we define an abstract model for a data link for our simulations based on a link layer queue at every node that is emptied and filled at a finite rate.

Both packets that are passed down from the higher layers as well as those that are received from another node are inserted into the link layer queue. This behavior reflects the fact that nodes in a wireless ad hoc network must transmit and receive over the same interface. This is valid both for a contention-based MAC such as IEEE 802.11 and a contention-free MAC, such as one based on TDMA. When a packet is taken from the queue, either to pass it up to the network layer or because it is sent to a neighboring node, the queue is blocked for the packet's transmit duration, which is calculated from the packet's length and the transmission rate. The next packet can only be removed from the queue after this time has elapsed. Each node's queue is emptied at a constant rate. Conceptionally, this could result from a fair scheduling algorithm that allocates an equal number of time slots to every node. Packets can only be lost due to queue overflow; packet errors due to the channel do not occur.

VI. SIMULATION RESULTS

By means of simulations, we have analyzed the performance of the proposed delay based gateway selection scheme and compared it to the hop count based selection and the utilization based solution of [12], given in Eq. 1. All simulations were

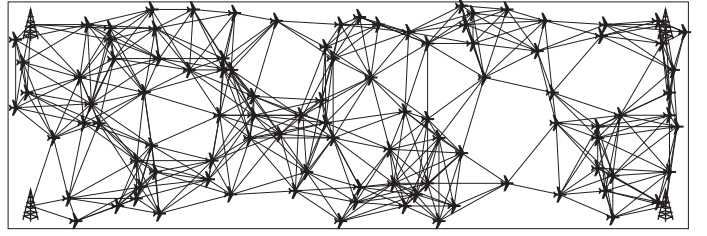


Fig. 4. Example topology of simulation scenario: 100 aircraft uniformly distributed in an area of 3000 km \times 1000 km with a transmission range of 370 km.

performed with the OMNeT++ simulation platform [14] and its INET suite for the simulation of communication networks.

To assess the load balancing capability of the different solutions, we make use of Jain's fairness measure [15]:

$$f = \frac{(\sum_i L_i)^2}{N \sum_i L_i^2}, \quad (4)$$

where the Load Index L_i of gateway i is calculated according to Eqn. 1, and N is the number of gateways. The fairness f assumes values between 1, corresponding to completely equal utilization of all gateways and $1/N$, if a single gateway handles the entire traffic.

In our simulations, we distribute 100 aircraft uniformly in an area of 3000 \times 1000 km, corresponding roughly to the size of the corridor used by aircraft flying between Europe and North America over the North Atlantic. One terrestrial Internet gateway is placed in the each corner of this rectangle. In addition, ten aircraft are assumed to possess a satellite link and also act as Internet gateways. The transmission range is set to 370 km. One example topology for these parameters is shown in Fig. 4. Since the time scale at which the topology changes is much larger than the time scale at which packets are generated and transmitted, we have simulated static topologies. The wireless capacity available to each node is 2 Mbps.

All aircraft generate packets according to a Poisson process whose mean λ is varied as a simulation parameter from 2 to 22 packets per second. Each aircraft's current Internet gateway generates downstream packets at the same rate. Since we expect users to download more traffic from the Internet than they upload, packets sent by the gateway have a size of 1024 bytes, whereas those sent by a mobile node are 256 bytes in size. Gateway advertisements of length 32 bytes are generated every 10 s. Although it is relatively large, this interval is sufficient in the aeronautical case that we are considering, due to the very large transmission range and low relative velocity of the aircraft.

The resulting Packet Delivery Ratio (PDR), average packet delay, and fairness of the gateway selection schemes are shown in Fig. 3 for the hop count based and utilization based solutions, as well as for our proposed delay based solution. The delay based solution has been simulated with hop count threshold $\delta_h = \{0, 1, 2\}$. The packet delay is measured between the aircraft and the ground, i.e. the terrestrial Internet gateway or the satellite Earth station. The satellite links are

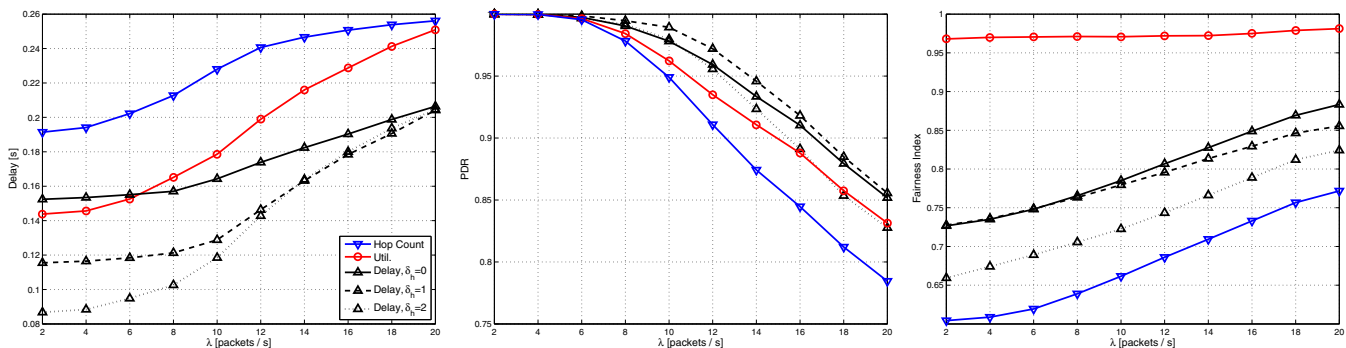


Fig. 3. Average delay, PDR, and fairness achieved by the hop count, utilization, and delay based GW selection schemes

assumed to provide infinite bandwidth and add a constant propagation delay of 240 ms. For each point, 500 randomly generated topologies have been simulated.

It can be seen that our proposed solution succeeds very well in directing traffic away from the satellite gateways when the traffic load allows, resulting in a significantly lower average delay than the other two solutions, which are completely agnostic of the satellite link's high delay. This difference is of course caused by the large delay of the satellite links; Low Earth Orbit or Medium Earth Orbit satellites will experience a significantly lower delay. A larger hop count threshold δ_h leads to less delay, especially at low load, since more gateways are included in the candidate set \mathcal{H}_c , and dedicated air/ground gateways will be preferred. This effect is also reflected by the fairness index of the delay based selection, which decreases as δ_h increases. Shifting the traffic away from the satellite gateways at low load does not lead to a lower PDR than the hop count or load based solutions. However, both $\delta_h = 0$ and $\delta_h = 2$ lead to a lower PDR than $\delta_h = 1$.

As could be expected, the utilization based scheme manages to balance the offered traffic among the gateways very well, leading to a fairness index very close to one. The low fairness index of the hop count based solution can be attributed to the random distribution of the aircraft acting as opportunistic gateways. With hop count based selection, a randomly placed opportunistic gateway will in general attract more traffic than one of the dedicated air/ground gateways, which are placed in the corners of the simulated area. At first, it appears surprising that the fairness of the hop count scheme depends on the offered traffic load. However, as the traffic load increases, more and more gateways will begin to become fully loaded with traffic and eventually saturate, thereby automatically decreasing the level of unfairness.

VII. CONCLUSION

In this paper, we have proposed a new Internet gateway selection scheme for an aeronautical ad hoc network, based on the estimation of the packet delay. By means of simulations, we have shown that the proposed algorithm outperforms more common solutions based on the hop count and gateway utilization, especially concerning the mean packet delay.

Future work will assess the performance of the proposed gateway selection strategy under more realistic conditions. This includes node mobility patterns that are based on real aircraft flight data, as well as a detailed implementation of the underlying link layer, instead of the abstract model that has been used here.

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