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Access and Routing in Aeronautical Ad-hoc Networks

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Abstract *Aeronautical Ad hoc NETWORKS (AANET) have been proposed in previous studies as an alternative to cellular or satellite transmissions for “datalink” communications between commercial aviation aircraft in flight and air traffic services on the ground. After an introduction on the specificities of civil aviation communications, we present the channel access and routing challenges for AANETs. We finally propose an innovative communication architecture for AANETs.*

A. INTRODUCTION

The commercial air traffic seems to have followed a steady growth over the past year, and is expected to keep growing in the coming years. In order to better handle this increasing amount of aircraft, new applications and services are being developed and implemented. Most of these new services rely on digital communications between aircraft and ground-based control. However, the increase in the number of aircraft and deployment of these new applications should saturate current communication communication systems by 2020 [18]. New air-ground datalink communication systems are thus needed to cope with this traffic growth.

In this context, ad-hoc networks are an emerging communication system that could handle a significant part of this growth [3].

Previous studies have already been conducted on the feasibility of AANET over oceanic and continental areas. Especially, [3] provides interesting results. For example, it demonstrates that a 350 km link range is enough to connect 95% over the north Atlantic airspace, and a 150 km range is enough to cover most of the aircraft in European continental areas.

The present paper presents works that focus on practical solutions to the challenges of medium access and routing in an Aeronautical Ad-hoc NETWORK (AANET).

The rest of this paper is organized as follows: Section B., adapted from [20], presents to the reader the specificities of aeronautical communications and some datalink communication system currently used or in development for civil aviation. AANETs are described in Section C. A description of data used for simulation is given in D. The problematics of medium access and routing are then introduced in Sections E. and F., with a highlight on the specificities of AANETs. The results of an early experi-

ment are presented in Section G. We finally propose in Section H. a communication system based on the content of the previous sections. Our conclusion and future work are presented in Section I.

B. AERONAUTICAL COMMUNICATIONS

B.1. Civil Aviation Communication Classification

The International Civil Aviation Organization (ICAO) is the international body regulating air travel. It defined four categories of communications regarding their safety level[7]. These can be grouped in two main categories :

- **Critical communications** : Air Traffic Services Communication (ATSC) which regroups communication between pilot and ATC to ensure the safety, speed and efficiency of the flight, and Aeronautical Operation Control (AOC) which are communications used by airline companies to communicate with aircraft (e.g. fuel levels, engine maintenance messages...).
- **Non critical communication** Aeronautical Administrative Control (AAC) and Aeronautical Passenger Communication (APC). AAC are neither linked to the safety nor the efficiency of the flight. Examples of AAC are informations about passengers (list of passengers, connections), special diet requests , hotel booking for aircraft crew... APC are services provided to passengers such as web browsing or phone calls.

ICAO defined very stringent rules for critical communications. For example only some dedicated frequency band can be used, and they must rely on dedicated systems. Critical communications must also meet very specific Quality of Service (QoS) requirements in terms of availability, continuity, integrity and transaction time. These regulatory constraints only apply to critical communications, even

if non critical communication must follow their own QoS (e.g. jitter for VoIP). The equipments aboard aircraft are also physically different to ensure a strict segregation between critical and non-critical communications.

We will only consider critical (ATSC, AOC) communications in the rest of this paper. Eurocontrol, the European organization for the safety of air navigation, has specified in [6] a pool of critical applications for future systems. These are based on sporadic message transmissions, and we are using them in the rest of our work to model application data traffic.

B.2. Traditional Communication Systems

Data link communication are used since the early 80's for air to ground communications. We list here some technologies currently used by civil aviation to communicate with en-route aircraft, and some technologies foreseen to be deployed in a near future.

Cellular Systems. Cellular systems provide a direct link between the aircraft and a ground station. With the exception of the High Frequency DataLink (HFDL), all these cellular systems are limited to a line-of-sight (or lower) range, thus requiring the deployment of a large ground infrastructure to cover a region. They are furthermore unable to cover oceanic flights far from the shores. Despite these drawbacks, they offer a reliable service at lower cost than satellite-based systems, and are suitable for numerous continental flights.

Satellite-based Systems. Satellite systems offer a link between two transceivers (an aircraft and a control center for example) by using satellites as relays. A satellite-based system provides wide coverage and relatively high speed links, but at the expense of cost. Main types of satellites are on geostationary earth orbit, which appear on a fixed position in the sky and cover one third of the Earth, and on Low Earth Orbit (LEO). The drawback of the geostationary orbits are high delays due to the distance, and a lack of coverage of the polar regions. A satellite on LEO will have a lower delay and can cover polar regions, but will appear moving in the sky, thus requiring a whole constellation to enable a continuous coverage. It has also to be noted that the integration of a high-gain antenna (required for high-speed connections) on an aircraft is a complex and costly task, adding mass and drag to the aircraft.

Conclusion on Traditional Communication Systems. Table 1 summarizes the main properties of communications systems currently used or in development for critical applications in civil aviation.

We want to put forward the offered capacity and covered areas. These values are indeed unusual for most of today's networks where high capacity means often several megabits per second and the maximum cell size for wireless networks is several kilometers. These must be kept in mind when studying the performances of communication systems designed for civil aviation critical communications.

Communications during oceanic flights (or over remote continental areas) require generally at least two communication systems to ensure the QoS for critical communications, which can be, for these areas, HFDL and satellite link. Furthermore the only satellite system available above polar regions (latitude higher than 70°) is Iridium. In this context, AANET would be an additional communication system rather than a standalone alternative.

C. AERONAUTICAL AD-HOC NETWORKS

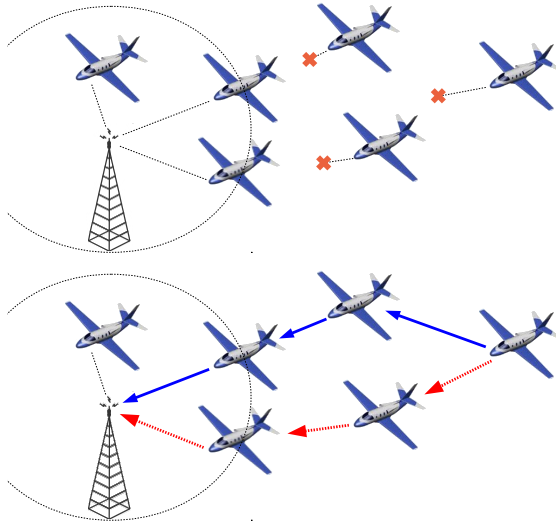


Figure 1: Illustration of cellular network (top) and AANET (bottom)

Ad hoc networks are often opposed to cellular networks, in which a central infrastructure manages the communication for every node within range. In the latter, nodes can't communicate if they are out of range from the relay. An ad hoc network is a wireless decentralized network in which every node can relay data, in addition to their classic role of data sender and data receiver. Ad hoc networks have multiple applications, including wide area monitoring with wireless sensors, emergency or military communication infrastructure, communication between mobile nodes (MANET, Mobile Ad hoc Network, which includes communication between vehicles in VANET, Vehicular Ad hoc network). AANET can be considered as a subclass of MANET, in which the considered mobile nodes are aircraft. For an aircraft, it means that other aircraft may relay its communications to the ground station. In this paper, AANETs are considered for air-to-

Table 1: Example of performances for several communication systems for civil aviation

System	frequency band	Offered capacity	range / coverage	operational status
HFDL [1]	HF	1.8kbit/s per ground station	2500 km	active
VDL mode 2 [1]	VHF	31.5 kbit/s per ground station	400 km	active
L-DACS	L	200 kbit/s per ground station	400 km	under test
InmarSat aero L	L	1.2 kbit/s per aircraft	for lat. under 70°N/S	active
InmarSat aero H	L	10.5 kbit/s per aircraft	for lat. under 70°N/S	active
Iridium	L	2.4 kbit/s per aircraft	global	active
IRIS	L	dozens of kbit/s per aircraft	for lat. under 70°N/S	expected 2020

ground communication even if they potentially allow air-to-air communication as well.

Expected advantages

- Better coverage : as presented in fig. 1, the coverage of an AANET can be much greater than the associated cellular coverage with the same amount of ground stations.
- Robustness : because the network is autonomous, it must be self-configuring and self-healing. The resulting network will be able to reconfigure itself in case of disruption, which increases the robustness of this communication system. Figure 1 gives also an example of robustness brought by multiple possible routes: if any node on the blue path fails, the dashed red one can be used.

Expected drawbacks

- Throughput : Even if only a few ground stations are required to ensure connectivity, they may be the bottleneck of the network and the number may become the limiting factor for the overall network throughput.
- Connectivity : because data is relayed by other aircraft, the connectivity is heavily dependent on the airspace density. If there are not enough aircraft in the whereabouts of a particular node, this latter may not be able to find a multi-hop path to relay its messages to the ground.

D. EXPERIMENTAL DATA FOR COMMERCIAL AVIATION

To our knowledge, other studies about AANET were conducted using simplified flight data, often the shortest path between the departure and arrival

airports. Mainly because of the wind conditions (high altitude jet-stream), this approximation could lead to errors up to several thousands kilometers [20]. Besse et Al. were the first to use actual flight data based on position report and/or radar measurements provided by Eurocontrol to reproduce actual aircraft movements[3][5]. We are using this method in the rest of our work.

E. CHANNEL ACCESS

The link layer handles node to node communication. When several aircraft within radio range of each other have data to send at the same time, the MAC layer is responsible to avoid collision between concurrent frames.

AANETs have, in addition to the traditional issues other network have, specific challenges. Their Ad-hoc natures forbid the use of a central coordinating entity. It renders also time synchronization difficult and resource-consuming. The fact that AANET nodes are airliners implies that they are moving (with speeds up to 1000 km/h) has consequences on radio receiver due to the Doppler effect. Finally, the wide range of distances involved (from 300 m to several hundreds of kilometers) adds also difficulties in radio signal decoding.

E.1. Classification of Solutions

Access methods are traditionally classified by the physical properties used to discriminate signals :

- Time division multiple access (TDMA) ensures collision-free transmissions by assigning one time slot to each frame.
- Frequency division multiple access (FDMA) uses different radio frequencies to allow simultaneous transmissions.
- Code division multiple access (CDMA) uses signal spreading and processing to create vir-

tual channels and prevent frames collision. Several overlapping frames can be recovered under certain conditions if they are spread with orthogonal spreading sequences.

In addition to this, access protocols can be put in two different categories according to their philosophy:

- Contention free protocols rely on negotiations between a sending node and a managing node (or its peers in the case of an ad-hoc network) to prevent collisions.
- Contention based protocols do not require coordination between nodes but use instead techniques such as channel sensing to avoid collisions.

Contention-based CDMA is promising for ad-hoc networks because the lack of coordination is desirable in an ad-hoc environment (no need of managing infrastructure) and the collision recovery allows a better use of the channel capacity (up to 1.5 times the capacity of TDMA and 4.6 times the capacity of FDMA in cellular systems [8]). However, it suffers some problems, especially the question of the code attribution for each transmission. Another problem is due to the asynchronous nature of uncoordinated ad-hoc transmissions. Because of that, spreading sequences can not be rigorously orthogonal and Multiple Access Interferences (MAI) will occur [2]. As consequence, ad hoc networks are subject to the near-far effect: a strong signal may hide a weak signal and prevent reception of the latter even if they are using different spreading codes. Such power distribution can easily be observed in AANET because the distance between aircraft ranges from 300 m to several hundreds of kilometers.

A previous study [2] has also concluded that CDMA is a suitable choice for AANET. It gives valuable informations on the radio layer and the required range, but it does not provide practical answers to the problems of code attribution and near-far situations.

F. ROUTING

The network layer ensures end to end communication. The routing algorithm of this layer is crucial because it determines the "path" (the sequence of relays) from the source to the destination. Compared to other subclasses of MANETs, AANETs present also some specificities that complexify the design of routing algorithms:

- The nodes are mobile, with speeds up to 1000 km/h.
- The network is large, both geographically (several thousands of kilometers for transatlantic routes) and in number of nodes (several hundreds).
- The system must be distributed.

F.1. Classification of Solutions

Several aspects can be used to categorize a routing algorithm. In order to keep this paper concise, only the most important are presented here:

- Design philosophy: A routing algorithm can be proactive (i.e. routes are computed before a node actually needs them) or reactive (i.e. routes are computed on-demand).
- Delay tolerance: see section G..
- Structure: in a flat network every node has the same role in the network, whereas in a hierarchic network some nodes have a specific role.
- Routing metric: the metric that the routing algorithm will try to maximize or minimize in order to favor a specific behavior: number of hops, geographic distance, route stability, load balancing...

These categories are not exclusive. A routing algorithm can be put in hybrid categories (e.g. the default behavior in ARPAM is reactive, but it is proactive to maintain the routes to some gateways [9]).

G. DTN ASSESSMENT

A Delay Tolerant Network (DTN, [19]) is a network specifically designed to take into account delays that could happen during a message transmission. In the case of AANET, these delays are due to the disruptions in the network: because of the node movements, some links may suddenly become unavailable, and return to an available state after a few moments. In order to assess if DTN algorithm could be useful in AANETs for commercial aviation, we used the following methodology: we derived from the aircraft position data presented in Section D. a graph whose nodes are the aircraft, and whose edges are the links available between two aircrafts. We considered that a link could exist between two aircraft if the distance between them was inferior to a threshold. In order to increase the number of disconnections, this threshold was set to 200 km, a value deliberately lower than the value required to ensure a reasonable connectivity (350 km). The goal was to assess the ability of DTN to recover the loss of connectivity due to the shorter range.

We considered that an aircraft is connected to the ground if a path existed in this graph between an aircraft and a ground station at a given time. The connectivity of the network is defined in this case as the ratio of connected aircraft to the total number of aircraft. The delay tolerance was simulated by considering losses of connectivity lower than a tolerance threshold not as full disconnections. During these transient losses of path to the ground, the aircraft was not considered disconnected. The results for several thresholds are presented in the following table.

Table 2: DTN connectivity improvements

Tolerated delay	Average connectivity
0s	49.0%
10s	49.1%
100s	49.6%
1000s	56.2%

A delay tolerance of 10s, which is already a high delay, increased the average connectivity by a mere 0.1%. Significant improvements were only observed for tolerance values too high for the majority of applications regarding their QoS requirements. We will thus not consider DTN routing in the rest of our work.

H. PROPOSED ARCHITECTURE

Based on an extensive bibliographic study, we propose to use in AANETs a communication system based on both RP-CDMA with partition spreading and trajectory-based routing.

H.1. RP-CDMA

Random Packet CDMA (RP-CDMA) [17] is a contention based access method relying on code division and multi-packet reception to allow multiple accesses.

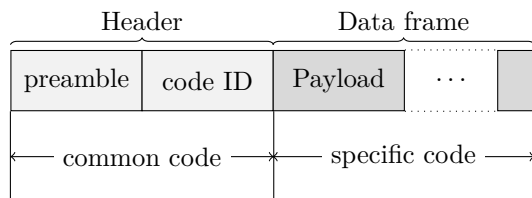


Figure 2: Structure of a RP-CDMA packet.

The structure of the RP-CDMA packets is presented in fig. 2. The header part is composed of a fixed preamble and a code identifier, both spread with a unique spreading code common to all packets. The preamble is used to detect the beginning of a packet and allow precise timing measurements. The *code ID* field identifies the code used to spread the data frame. This code is randomly and independently selected by the sender. Thus, the header contains all the information required to allow the receiver to decode the data frame and solves the code allocation problem. Consequently, RP-CDMA is only limited by the collisions on headers as long as the collision recovery capacity of the multi-packet receiver is not exceeded.

The idea behind this packet structure is to transmit headers on a separate channel, defined by the common code. The header may thus interfere only with other headers, and the probability of these collisions is kept low by using small headers. Because

each payload is transmitted on a specific channel (defined by the specific code), they should not interfere with each other unless they are using the same code. The probability of having two concurrent payloads using the same code is thus dependent on the number of available spreading codes and on the channel occupation. The channel separation in CDMA rely on the ability to decode several packets received simultaneously, which is called Multi-Packet Reception (MPR). Several technologies for MPR in RP-CDMA are proposed in [11]. Amongst them, partitioned spreading [10] is a very promising technology, allowing the recovery of a high number of concurrent messages and dealing well with Multiple Access Interferences (MAI). A multistage partitioned spreading demodulator implementation has been evaluated in [4], and it has been shown that partition-spreading CDMA is highly resistant to near-far effect [16].

With MPR, the nodes are able to receive several packets at once. Several studies presented in [12] show that Multi Packet Transmission (MPT) would improve the performances of the system. Mortimer et Al. propose in [13] a MAC protocol to make use of MPT and MPR with RP-CDMA.

Thanks to its uncoordinated nature, RP-CDMA is particularly relevant for Ad-hoc networks. CDMA had already been proposed for AANETs, and RP-CDMA with partition spreading answers quite nicely to the problems of code attribution and near-far effect.

H.2. Trajectory based routing

Trajectory based routing (TBR), as presented in [14], follows the position centric routing paradigm. It is an improvement of cartesian routing. In cartesian routing, the destination of a message is a geographic position, and intermediate nodes forward this message along a shortest-path trajectory. In TBR, a geographic trajectory is computed by the sender. It is carried by each message instead of a single destination, so that the relays are able to forward it on a route as close as possible to this trajectory (see fig. 3). This has several advantages:

- Because the trajectory is specified by the sender, it allows very simple path diversity: sending a message twice but with different trajectories will increase the chances of delivery.
- The sender doesn't need to know the position of other nodes than the destination.
- The avoidance of specific regions (low aircraft density, obstacles...) can be handled directly by the sender.
- It allows efficient broadcasting (messages that follow the edges of a tessellation).
- It enables also geocasting (geographic broadcasting).

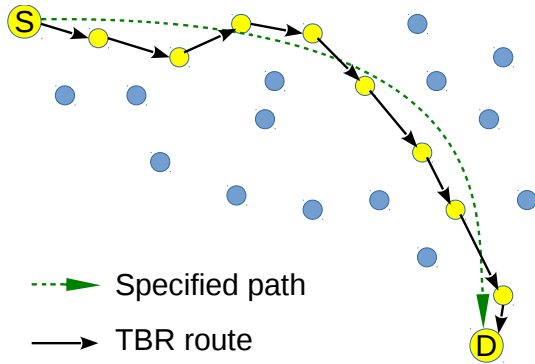


Figure 3: Illustration of TBR.

TBR was originally proposed for networks with high node density (e.g. smart dust in [14]). It may seem contradictory at first to use it for AANET because the node density is not guaranteed to be high enough, but there are several informations that can be used to cope with this problem:

- Authorities are deploying systems to monitor in real-time the position of aircraft (e.g. from space [15]). We can safely assume that the ground stations will be able to use this information to build a map of aircraft density, and use that map in order to compute the best trajectories for uplink messages.
- This map can be broadcasted to the aircraft, so they can compute the best downlink trajectories as well.
- If this map is unavailable, the fact that most

aircraft follow predetermined airways can be used. High aircraft density are indeed most likely to be found near major airways.

Despite its promising features, TBR has not yet been studied in AANETs. One of the goals of our work is to fill this gap in the knowledge of routing protocols for AANETs.

I. CONCLUSION AND WORK IN PROGRESS

We have presented in this paper the result of an extended bibliographic study on medium access and routing in AANETs, as well as an experimental assessment of the use of DTN in AANETs. These have brought us to propose RP-CDMA and trajectory-based routing as the architecture for an AANET communication system for commercial aviation.

A simulation model of RP-CDMA has been written in the simulator Omnet++, and the study of its performances should be over in the coming weeks. Once this study is over, the RP-CDMA model will be included in a broader Omnet++ model where we will implement a TBR algorithm. This algorithm will be adapted to make use of the specificities of commercial air transport, such as the knowledge of aircraft positions thanks to an external system or the fact that aircraft follow precisely defined routes. We will then compare TBR performances with state of art MANET routing algorithms in north Atlantic oceanic and continental European areas. These simulations will be conducted with real aircraft position data and a realistic traffic model.

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