Applicability of Mobile Ad Hoc Networks in an Aeronautical Environment

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***Abstract*— Aeronautical Communication are currently based on the OSI protocol based ATN standard, which does not allow aircraft to communicate directly with each other. Several studies are underway within the aeronautical community to replace the OSI-based ATN with the more efficient and widespread TCP/IP protocols. This paper follows this trend but takes it step further and proposes the incorporation of Mobile Ad Hoc Network functionality show as to allow direct aircraft to aircraft communications in a dynamic environment, enhance existing services and provide the infrastructure for future ones. Additionally high speed, directional data links are utilized to offer higher data rates. To achieve this, the TCP/IP protocol stack has been enhanced with functionality necessary for the aeronautical MANET. The new stack includes an enhanced ad-hoc routing protocol, a new addressing scheme and a mechanism that allows for the dynamic management of terminals in a node. Simulations results are provided that provide proof-of-concept for the new aeronautical telecommunications network architecture.**

***Keywords*—Mobile Ad Hoc networks, high speed data links, aeronautic communications**

I. INTRODUCTION

Today aeronautical communications are dominated by two systems, the Aircraft Communications and Reporting System (ACARS) and the Aeronautical Telecommunications Network (ATN). ACARS [1] is a data link system which allows for messages sending between an aircraft and a ground system. The messages are character-oriented and bit-oriented transfers are only supported through proper modification. ACARS allows for the sending of automated messages (e.g. performance and fuel status issues), as well as the sending of typed messages from a keyboard. ACARS has been extended to allow for Air Traffic Control applications, which require an end-to-end integrity check and to send messages to multiple ground terminals. Still despite these extensions, ACARS is an obsolete system which, is slowly being replaced by the newer but still limited ATN [2].

The ATN is a global aviation standard telecommunications network established by ICAO, and is intended to provide seamless ground-to-ground and air-to-ground communications. The ATN has slowly been implemented but even before it's use was in full swing its limitations were clear. The ATN is based on OSI protocols which are known to be complicated and cumbersome. Additionally there is very little experience and equipment that utilizes them. IP protocols in contrast are much more lightweight and they have been the mainstay of most networks for several decades. Naturally this has lead to the availability of extensive know-how and ample, cheap off the shelf equipment. These advantages have drawn the attention of the aeronautical community. IPv6 is the obvious choice for the new architecture since it overcomes all the limitations of IPv4 and most importantly provides ample addressing spaced, allows for efficient addressing schemes and enables reliable, QoS-based packet flow. These characteristics are of paramount importance for the aeronautical community and were some of the main reasons for selecting OSI over TCP/IP in the first place.

To accommodate for the expected growth in aviation over the next decades, ATN must give its place to a new, innovative and flexible architecture, which will allow for enhanced data flow and enable a quantum leap in ATM/CNS information dissemination. Managing the increased number of aircraft in combination with more demanding passenger-related services will see the requirements for information generation, gathering, and sharing among the various involved entities rise dramatically.

The ATENAA project [3] investigated the potential of a new architecture, based on Mobile Ad Hoc Networks (MANETs), which acts as the glue between innovative data link technologies such as Outer Optical Links (OOL) and Ka-band air-to-air communications. MANETs have been investigated intensely in the past years, however they have not found their way in commercial applications until now. However their use in military systems has been quite widespread. MANETs can be a catalyst in the development of an advanced aeronautical network. In this concept the aircrafts themselves form a self-organizing network in combination with any ground or other infrastructure where and if it is available.

The rest of this paper is organized as follows: Section II outlines the operational and system requirements of the aeronautical telecommunications network. Section III describes the network architecture proposed, while section IV describes the internal architecture of a node. Section V presents simulation results which provide a first insight into the feasibility of this architecture. Finally section VI reviews our work and provides guideline for future development.

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Table 1: Flight Service Requirements

Service Type	Through-put	Availability	Latency	Criticality
CNS/ATM	Low	Maximum	Low	High
AOC	Low	Medium	Medium	Medium
APC/IFE	High	Medium	Medium	Low

II. OPERATIONAL AND SYSTEM REQUIREMENTS

Defining the operational requierements is an important step in developing the concept of a Mobile Ad Hoc aeronautical network.

An aeronautical network may consist of several types of nodes which are extremely diversified both in their requirements and their capabilities. The most common type of nodes will be aircraft, which can range from big, transcontinental airliners to small leisure craft. A large commercial aircraft with hundreds of passenger will require significant amount of bandwidth for In-Flight Entertainment service, while a small aircraft none at all. However the commercial plane will most likely boast advanced communication equipment using sophisticated smart antennas. This paper assumes a commercial airplane to be equipped with the standard aeronautical VHF data-link, which has been the workhorse of the civil aviation community for several decades, a microwave, high speed directional data link, which utilizes phased array antennas and a free space optical link which will be used for long range, high bandwidth links when the aircraft is in the en-route flight phase. A plane will most likely be equipped with more than one terminal for each of the directional data link types, but this is not a necessity.

Microwave links of these types are already used in military applications [4]. Free space optical terminals for aircraft to aircraft and aircraft to ground communication are under development within the ATENAA project. Naturally optical links will only be used during the en-route phase since clouds would render them useless in lower altitudes. Additionally optical terminals use mechanical tracking which limits their acquisition time to several seconds. This suggests that the OOL is to be used for long-lasting connections that transfer large amounts of data. In contrast smaller private planes are expected to carry only the VHF data link and one directional link at most. It should be noted that the proposed network is not limited to the data link types proposed here. These are merely representative of some state-of-the-art data link available and considered for use by the aeronautical community.

Besides aircraft there are three more node types in avionic networks. The first one of those are ground stations, which include airports and various types of relay stations, that are exist today. It should be noted however that one of the goals of deploying a multi-hop ad hoc network in the aeronautical environment is to reduce or ideally eliminate the need for ground stations. In this architecture we take ground stations into account but do not consider them necessary for network operations. Airports are assumed to have available similar equipment as commercial airliners. Ground Stations should have equipment similar to that of small planes. Another node type is the satellite, various types of which are available for aeronautic communications. Satellites offer decent throughputs but at a very high price, which is something that airliners and communications operators are trying to avoid. Additionally so far no satellites with optical transponders are available and the launch of new ones, properly equipped for the avionic network would be extremely costly. Thus satellites are considered as part of the network but their use will be limited to areas were other means of communications are unavailable. The final node type is the High Altitude Platform (HAP) [5]. HAPs operate in the stratosphere, 17 -30 km. above the ground, well above aircraft but below satellites. Their position is stationary and thus they combine the benefits of MEO and LEO satellites, while avoid their drawbacks. HAPs are expected to be deployed and available for commercial services within ten years. While their presence can be very useful, since they can essentially form a backbone network in the sky, it should be expected that HAP coverage will only be available in densely populated areas where their cost can be justified by additional applications. Thus it is most probable that most areas of the global avionic network will have to operate without HAP availability. HAPs are assumed to have communications capabilities ranging between those of commercial airliners and airports. This means a VHF link and several Ka antennas and Optical terminals.

Another important element that must be considered in the design of the network architecture is the services that must be offered. Table I shows the main flight service categories along with their main characteristics. Air Traffic Management (ATM), Surveillance and Navigation services are the most critical but require little bandwidth to operate efficiently. A next generation VHF link should be able to serve all these applications easily. Airline Operation Center (AOC) services are not time critical but require more bandwidth and are more important than Aircraft Personal Communication (APC) and In-Flight Entertainment (IFE) services, which might be the least critical but have the highest demand on throughput. During the take-off and climbing phases only the VHF data link is reliably available for use. The Ka-band links availability is subject to weather conditions but may be should be available with limited range and throughput, while the OOL will almost certainly be obscured by clouds and other atmospheric disturbances. During the en-route flight phase passenger services are available and thus the OOL and the Ka-band link are expected to be used for the bulk of data traffic. However some CNS/ATM-related time critical information will continue to use the VHF link to reduce latency or broadcast data packets, something difficult to achieve with directional terminals.

III. NETWORK ARCHITECTURE

The proposed avionic network architecture takes into account the peculiarities of the aeronautical environment and uses them to its advantage to ensure maximum information throughput. MANET are integral to this concept, allowing for the A/C to assume the role of a intermediate node thus greatly extending the range of communication and creating a flexible truly global solution.

There are several challenged in utilizing MANETs in this concept that have rarely (or not at all) encountered in the available literature. The aeronautical MANET is to be implemented in a 3D environment, with nodes moving at high speeds over large distances. This is in stark contrast with what has been investigated so far in the literature. Additionally each node utilized multiple wireless data links, some of which are directional in nature. Power concerns are limited since A/C can be considered to posses an abundance of power. Finally, as evident from the discussion in section 2, the environment for which the network is designed is not a pure ad hoc environment, but includes a number of fixed nodes (airports, ground stations and HAPs). It is important for the defined architecture to be able to take advantage of these nodes to allow for optimal packet routing. It should be noted that the distribution of these fixed nodes is anything but uniform. In areas with dense population and air traffic, the number of fixed nodes is quite large, while in other areas, especially over the oceans, it may be non-existent. Areas with a high fixed node density have and will continue to have the largest amount of air traffic, which is fortunate since their existence will allow for the creation of a communications backbone that will enable the network to sustain the increased number of nodes (several thousand in areas like Europe and North America).

Besides the need for reliable communications and support in dense traffic areas, the proposed architecture must be able to support low density areas in which no communications infrastructure may exist. This means the proposed network architecture must support the creation of isolated mobile ad-hoc sub-networks. These sub-networks will originally be isolated, but may in time acquire a connection to a gateway node. Figure 1 illustrates the proposed network architecture, which consists of aircraft (which may be of either type, as defined in section 2), airports and HAPs. Satellites have been omitted, since the ultimate goal is to achieve adequate performance without having to utilize them. The ground stations and airports form a stationary backbone between them. Additionally in areas where HAP density is adequate a second fixed backbone may be created.

The inherent limitations of each data link utilized in the avionic network dictate its use and impose constraints on the network architecture. The VHF data link is the most reliable but its limited bandwidth does not allow it to serve all flight service types. However it could be used to transfer the more time critical applications. The Ka-band link uses phased array antennas that can acquire a moving target in milliseconds. This suggests that Ka-band links may be used for temporary ad hoc connections since each terminal may be retargeted to another node swiftly. In contrast the OOL's slow acquisition time suggests that it should be used for backbone connections between aircraft and gateway nodes and not for aircraft to aircraft connections. To this end we allow a traffic flow to "commit" an optical terminal. When the optical terminal has been committed to a specific flow, it continuously tracks the destination node for that flow (as long as it remains within the terminals field of regard of course) until it is released.

Choosing the proper addressing scheme for the avionic network represents an important challenge. The IPv6 addressing scheme allows for very flexible addressing strategies, with multiple levels of hierarchy. The most reasonable approach to follow would be to assign multiple levels of hierarchy on a geographical basis. Despite the fact that addressing needs are vastly different in various areas of the world (e.g. in Africa and Europe), and thus an even distribution of addresses in not the most efficient solution, IPv6 provides ample addressing space, more than anything the aeronautical community will need in the far future. The addressing regions will be divided per continent and in turn this will be divided into sub-regions. The levels of hierarchy may vary from region to region.

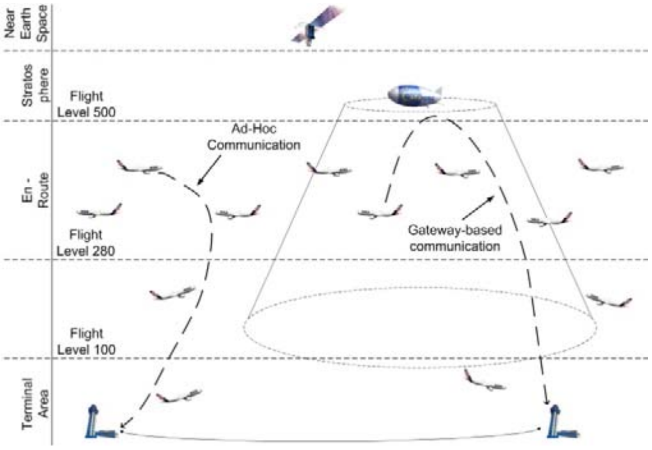

Figure 1 – Avionic Network Communication Scenario

The challenge stems from the presence of a large number of mobile nodes, which are expected to traverse great distances, crossing several addressing regions in their path. Aircraft will always originate from an airport and thus will receive an address which will correspond to the addressing region for that airport. During the course of a journey the aircraft will pass through several addressing region which may be totally irrelevant to its initial one (this will be particularly true for long transcontinental flights). Using a system similar to Mobile IP [6], where traffic will be routed through a home agent, is unacceptable due to the distance (both physical and logical) that will separate the two nodes and the large amount traffic that may need to be forwarded. Maintaining the same address is a possible choice but will result in completely unoptimized routing entries and will negate the effort to provide efficient packet forwarding.

An improved solution, taking into account the abundant addresses available is to allow a node to have multiple addresses, one for each addressing region. This will balance the amount of addresses a node will have with the amount of routing entries that must be maintained for that node. A commercial airplane will in praxis never fly through more than three continents in one trip. The address assigned by the originating DHCP server should be persistent, while addresses assigned by regional servers in regions that the aircraft is traveling through should be temporary. When a new address is assigned by a regional server the routing entries in that region should be updated to include the correlation between the persistent address and the newly-assigned one.

IV. NODE ARCHITECTURE

One of the goals of the ATENAA project was to the design of a complete protocol stack that will allow nodes to efficiently operate within the specified network architecture. This requires us to make extensive modifications to several layers of the OSI protocols stack. Figure 2 shows the proposed protocol stack, focusing on the lower layers of the TCP/IP stack, mainly the network and data link ones. In the network we utilize IPv6 as the core protocol, however the most interesting components are the routing and auto-configuration algorithms.

Routing in MANETs has been at the focus of research in this area for the last ten years [7]. The output of this research has been an impressive number of protocols which can be mainly categorized in four areas: proactive, reactive, hybrid and cluster-based solutions. The network architecture defined in section 3 indicated that a hybrid solution is to be used. The use a reactive protocol is best suited to minimize routing overhead, since the inherent highly mobile nature of the avionic network will force a proactive protocol to constantly update the route tables thus prohibitively increasing the overhead. On the other hand the presence of fixed nodes that act as gateways encourages the use of a more proactive approach.

Another important consideration is the fact that the bulk of traffic on the avionic network will be between the aircraft and the gateway nodes, when such a connection is directly available. Only limited information regarding aircraft separation and other CNS/ATM services are expected to be disseminated among aircraft. Thus performance would be significantly enhanced if a route to at least one gateway node was readily available. The information could then be routed to the destination node via the ground network. This would reduce the number of route discoveries that the routing protocol would have to perform. Cluster-based algorithms are not suitable for this network because despite the fact that aircraft near a gateway behave like a cluster, traffic is not necessarily routed through the gateway (which plays the role of the cluster-head in this case).

The ideal solution would be a protocol that combines proactive and reactive functions. The only currently available protocol with such a feature is the Temporally Ordered Routing Algorithm (TORA) [7]. TORA is not suitable for such network topology with large number of nodes, because in case of dense networks the routing information overhead is sensible higher than the overhead produced by other protocols and the packet delivery ratio is extremely low in comparison with other protocols. To enable the avionic MANET a new routing protocol custom tailored to fit its operational requirements has been developed. This protocol is the ARPAM, and incorporates functionality from two well known MANET routing protocols, AODV [7] and TBRPF [7]. ARPAM bases uses mechanism similar to AODV for route discovery, but additionally utilizes part of TBRPF's proactive functions to maintain a valid path to at least one gateway node at any given moment. Additional innovations include the reduction of the transmitted HELLO packets used for route maintenance, by cooperating with the Data Link Layer of each terminal and the use of GPS information already available on aircraft for optimum route selection. The ARPAM protocol is described in more detail in [8].

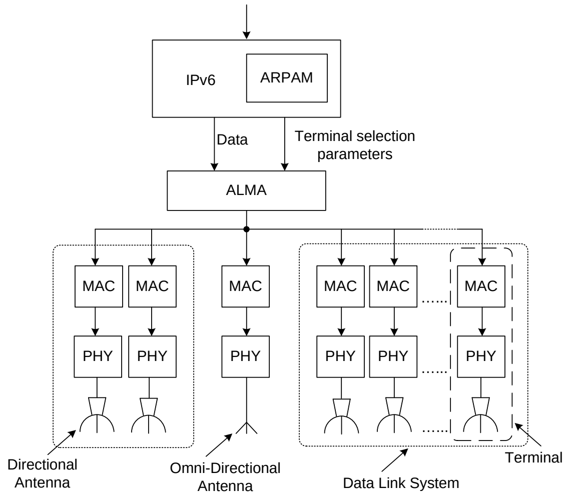

Figure 2 – Lower layers of the Aeronautical Network Node Stack

Auto-configuration is an important issue in MANETs. In the avionic network this problem is somewhat negated by the presence of gateway nodes which can act as DHCP servers. An additional consideration is the fact aircraft will always initiate their flights from airports and thus will always receive their address from the airports DHCP server. Fixed nodes are assumed to have predefined addresses. Aircrafts are assigned by ICAO a 24-bit unique address which can be used as a unique identifier. This 24-bit address will be embedded in the nodes IP address. This ensures that each node will have a unique IP address. In addition to the stateful auto-configuration method each node will be equipped with a stateless one. If a DHCP server cannot be reached then the stateless algorithm shall be employed.

One of the most important innovations found in the protocol stack of Figure 2 is the presence of a data link selection mechanism, name the Advanced Link Management Algorithm (ALMA) [9]. Most of the nodes types defined for this network utilize more the one directional terminals of the same type. These terminals will certainly have limited field of regard each, and thus each antenna will be able to cover only part of the horizon. Thus not all terminals will be able to communicate with all nodes at any given time, and a method must be provided for the correct terminal to be determined. ALMA assumes that the upper layers have already determined which data link system is to be used for the transmission, thus ALMA has to determine which terminal of each data link system to use.

Besides the obvious limitations stemming from the field of regard of each terminal, additional criteria are weighed in, like the availability of each terminal and the direction it is currently pointing to, as well as the tracking speed for this type of terminal. Additionally ALMA utilized the omni-directional VHF link that is assumed to be present in all network nodes, to achieve the alignment of the directional terminals. This is accomplished by performing an RTS/CTS style handshake, at first through the omni-directional link and then through the directional link. The RTS/CTS signals also include each nodes geographical position. This ensures that the geographical information is always up-to-date when a connection is to be established.

In the physical layer a few assumptions are being made to ensure their seamless cooperation with the Data Link and Network layers described above. More specifically it assumed that the range of the omni-directional link is at least equal to that of the directional links. This is required to achieve the successful alignment of directional terminals using ALMA at any transmission range. In the aeronautical network the VHF links used have a range of up to 200 nautical miles, which is more than sufficient. Future links are projected to have similar transmission ranges. The second assumption is that each terminal has its own Data Link layer and thus ALMA forwards the packets directly to that layer. It is possible for a data link system to have a unified Data Link Layer for all terminals but it should be able to interface with ALMA appropriately.

V. SIMULATION RESULTS

To estimate the performance of the proposed network architecture the protocol and subsequent node models were created for the OPNET simulator and then two operational scenarios commonly found in the aeronautical environment were simulated.

The modeling of the three data link systems was done to approximate their functionality, though their exact specifications are not yet known. The most promising candidate for the future aeronautical data link is the VDL-4 [10], however its usage has not yet been universally agreed. To avoid committing the project to a specific link technology, we modeled a generic VHF link which uses a 25-KHz channel (the aeronautical VHF band utilizes 4 25 KHz channel) to achieve a maximum throughput of 100 Kbs. This bitrate is significantly more than what VDL-4 offers (19.2 Kbps) but much less then future links promise (e.g. B-VHF [11] will offer up to 1 Mbs). The range of the generic data link is 200 nautical miles, which is on par with current and future aeronautical VHF specifications.

In these first trials node models with only one of each type of data link were modeled. The Ka-band data link was modeled using a phased array terminal, with a beam width of 5 degrees and a maximum throughput of 16 Mbps. Due to the difficulty of modeling an optical link in OPNET its behavior is approximated using an RF link which provides the same bandwidth (622 Mbps), a much smaller beam width (500 microrad) and reduced tracking speed, since the any optical terminal would have to be mechanically aligned with the target.

A. *Omni-directional oceanic scenario*

The first of the tested scenarios involves an oceanic corridor in which the planes fly in regular trajectories from the one side of the ocean to the other. The distance between 2 consecutive aircraft is defined in time units (7 minutes apart), which taken into account the typical cruising speed of a transatlantic A/C (around 870 km/h, which is the node speed used in this scenario) can be converted to a distance of a 101 km. The airspace is divided into two corridors located vertically and separated by 1000 feet. A/C in the one corridor fly towards one direction, while A/C in the other direction fly towards the other.

The scenario illustrated in Figure 3 attempts to capture this situation with 3 A/C flying towards the ground station and 4 A/C flying away from it. We assume that all A/C are equipped only with an omni-directional link. This scenario is representative of the envisioned mid-term aeronautical network, where most of the fleet will not yet have been equipped with directional data links.

The application tested is a weather maps request which is performed every 5 minutes for A/C relatively near the gateway (up to 500 km) and every 30 minutes for A/C that are further away. The file size ranges from 500 KB to 1 MB, which is typical of a compressed high resolution image.

Figure 4 illustrates the results from the performed simulations. The upper graph show the response times for A/C marked as A (the one furthest from the ground station), while the lower graph shows simple ping responses for the same A/C. These are included to investigate the connectivity as the airplanes move away from each other. The results illustrate the ability of the network to adapt to the rapid topology changes and serve the file requests. We see that the initial two requests require significant time to be served. This is expected as the limited bandwidth of the omni-directional link should be taken into account in conjunction with the fact other nodes request data at the same time and that A/C A is initially far away from the ground node and thus the data needs to be forwarded through multiple hops. When A approaches the ground station and starts request maps at 5 minute intervals, the transfer time is reduced significantly as the transfer only needs one or two hops and most of the other nodes are no longer able to reach the ground node, thus the channel is much less loaded.

A. *Oceanic directional link scenario*

The second of the tested scenarios involves transmitting large amounts of data from the ground station to a client A/C through several intermediate nodes. This transmission utilizes the directional links. This means that the links must be aligned using the algorithm previously described, using the omni-directional link as a signaling medium. Here 4 aircraft flying in parallel trajectories towards a ground station are employed. This attempts to represent a typical oceanic scenarios on which the planes follow each other in a narrow corridor from one coast to the other. Thus the flight level, velocity and separation distance of the A/Cs have been adjusted accordingly (35000 feet altitude, 900 km/h airspeed and 250 km distance between the A/C).

There two applications running on the server: the first is a medium traffic HTTP application which runs in the background between all the nodes and the ground station. This traffic emulates the load of typical ATM application which run in the background. The second is an FTP application which transfers the data using the directional link. The data are video files between 5-10 MBs in size. A new file is requested every5 minutes. This refresh time is typical for meteorological data

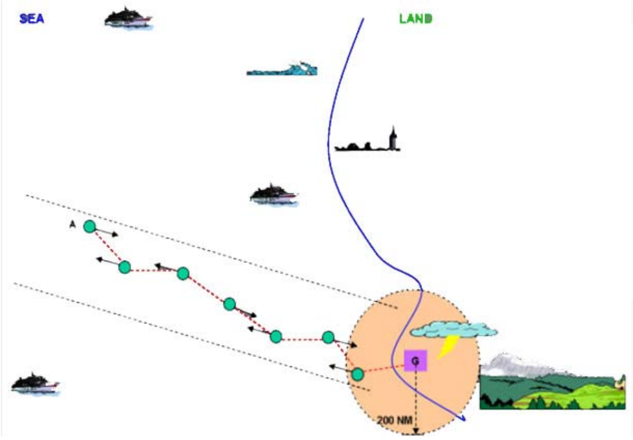

Figure 3 – Omni-directional oceanic scenario overview

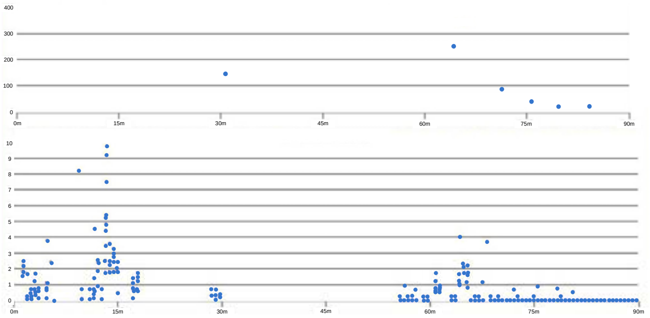

Figure 4 – Download response time and ping response vs simulation time for the oceanic scenario.

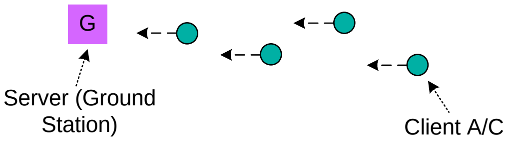

Figure 5 – Oceanic scenario overview

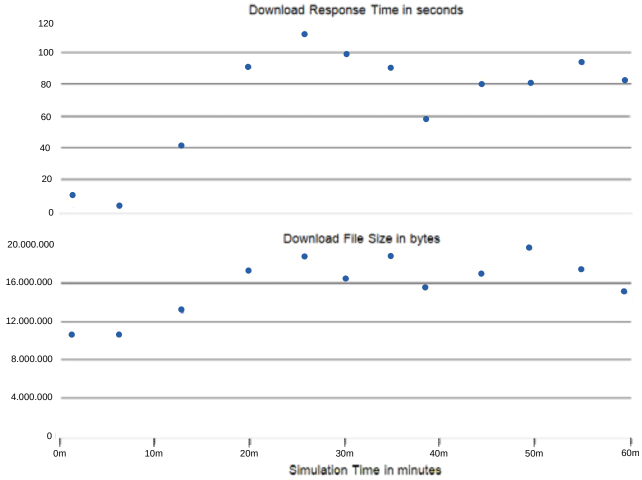

Figure 6 – Download response time and file size vs simulation time for the oceanic scenario.

applications, which currently however they consist of simple text information.

Figure 6 shows the results obtained from this scenario. The upper graph shows the amount of data transferred, while the lower graph show the time required to complete the transfer. The transfer size is proportional to the file size and remains within reasonable limits. The initial file transfer took a little more time than the subsequent one, despite them having the same file size. This was due to the need for initial antenna alignment, which was however performed swiftly without significant delay (additional to the pointing and acquisition time of the terminal itself). This means that the handshake process does not incur significant latency.

VI. CONCLUSION

This paper attempts to define an aeronautical mobile ad hoc network architecture. This architecture composes of the main elements found or expected to be found in future aeronautical environment. Additional the expected flight services and data link types that will or could be used have been explored. For developing the node protocol stack to enable this architecture state-of-the-art MANET literature was reviewed and the most suitable protocols were selected and used as inspiration for new ones custom-tailored to the avionic networks needs.

The preliminary simulation results allow us to be optimistic about the performance of our architecture. It has been shown that using the proposed network architecture, avionic network can both enhance its available services and meet its operational requirements for the coming 30 years. Future work will involve the definition of a QoS mechanism to efficiently access all the data. Additionally the addressing mechanism will be developed and tested.

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