Ad-hoc Routing Protocol for Aeronautical Mobile Ad-Hoc Networks

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***Abstract*-In this paper, we present a theoretical approach and the simulation results for an innovative Mobile Ad Hoc Network (MANET) routing protocol designed for the needs of aeronautical applications, particularly having the free flight concept in mind as an ultimate goal. The protocol we propose is the Ad-hoc Routing Protocol for Aeronautical Mobile Ad hoc Networks (ARPAM) and it is primarily based on AODV, an existing multi-purpose routing protocol for mobile ad hoc networks. The innovation of the ARPAM protocol consists in the exploitation of the geolocalization information made available by aeronautical applications, the use of proactive functions and an improved approach on the route maintenance.**

I. INTRODUCTION

In recent years there has been a tremendous evolvement of wireless networks that has been accelerated by the introduction of the IEEE 802.11 protocol. This led to the development of numerous technologies one of which being the Mobile Ad Hoc Networks (MANETs). MANETs are decentralized multi-hop networks that do not require any kind of network infrastructure, in order to provide the capability for the use of a wide variety of applications in civilian and military fields.

Bandwidth and connectivity restrictions in present aeronautical data communications are a matter of concern within regulatory authorities since these represent one of the bottlenecks for future aeronautical industry expansion. As an example the free flight concept is one of the most important innovations the aeronautical community intends to implement in the next 20-30 years. Its application will lead to several benefits like the reduction in the length of flight routes, cuts in operating costs and reduced environmental pollution. Currently defined aeronautical network technologies, such as Aeronautical Telecommunications Network (ATN) have difficulty in fulfilling free flight requirements and various efforts are ongoing to resolve these restrictions. ATN shortcomings include the use of aircraft only as end nodes, which means they must transmit their data packets through ground stations, prohibiting the direct communication between each other. This makes the dissemination of situation awareness information (necessary for free flight) practically unachievable. On the other hand the dynamic nature of MANETs allows nodes to form both Intermediate and End Systems that, coupled with communication data links, provide aircraft to aircraft and high bandwidth connectivity thus bypassing ATN limitations and accommodating the transit to the free flight. Using MANETs we truly expand the existing communication capabilities among aircraft and between aircraft and airports.

The need for a novel routing solution emerges from the lack of a protocol suitable enough for the aeronautical environment and its demands, such as the exploitation of the combination of novel directional high bandwidth data link technologies with the conventional and recently utilized omni-directional VHF data-links. Of course, directional links are much more suitable compared to their omni-directional counterparts in serving bandwidth consuming applications, in particular where long distances are involved such as in aeronautical applications. Additionally, existing multi-purposed unicast routing protocols lack the provision for handling geographical information, an important capability due to the high mobility of the nodes that make up the network.

With the Ad-hoc Routing Protocol for Aeronautical Mobile Ad hoc Networks (ARPAM) in combination with a data link layer selection algorithm, we attempt to utilize a wide spectrum of emerging and present communication technologies in order to support many different aeronautical operational scenarios. The data link selection mechanism makes sure that data is transmitted through the appropriate antenna while it also ensures that the directional antennas of the node are pointing to the right direction.

ARPAM is primarily an on demand and distance vector protocol which utilizes proactive functions in specific circumstances. It is based on former research done by C. Perkins et al. [1] on Ad hoc On demand Distance Vector (AODV) and by R. Ogier et al. in the Topology Dissemination Based on Reverse-Path Forwarding (TBRPF) [2] routing protocol. Based on the geographic information made available by external aeronautical applications, ARPAM discovers the shortest route based on various criteria like distance between nodes and the number of hops between them. Furthermore, ARPAM introduces an on demand route maintenance mechanism which in combination with the error reporting mechanism included in AODV protocol provides reduced routing overhead.

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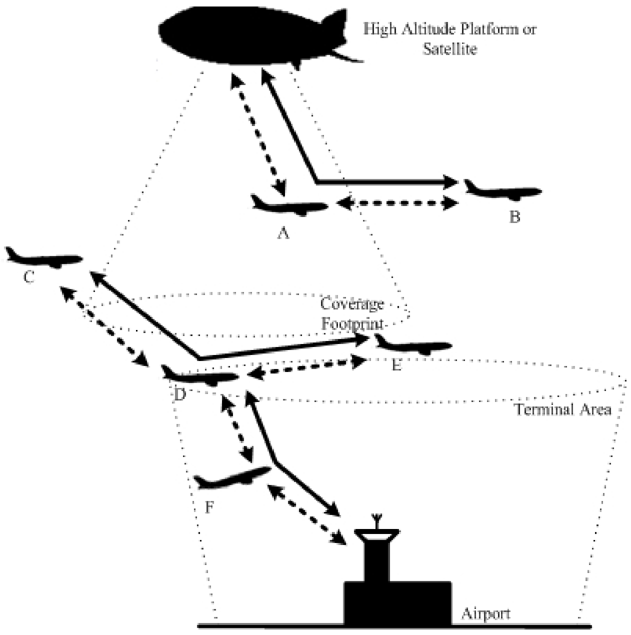

Figure 1. Network topology

II. NETWORK TOPOLOGY AND NODE DESCRIPTION

In order to provide a better understanding of the concept we would like to briefly present a proposed future avionics topology.

As it is illustrated in Fig. 1, the airspace is populated by airports, High Altitude Platforms (HAPs) [7] or satellites and aircraft, which act as network nodes. HAPs are either airships or planes, which operate in the stratosphere, 17 to 22 km above the ground, well above any normal aircraft but substantially below orbiting satellites. Airports, HAPs and satellites are referred to as backbone nodes and act as gateways to the Internet while satisfying high demanding aeronautical and in flight entertainment applications. Also they have specific coverage footprints and thus among them exist uncovered airspace areas. MANETs connect the aircraft which are not in coverage and create paths among them in order for each aircraft to be capable to communicate with a backbone node. Also, in order to satisfy the need for communication between two aircraft it is possible to satisfy air traffic control (ATC) applications bypassing the need of communication through an intermediate node like satellites and airports.

We consider that each aircraft is equipped with a single omni-directional antenna similar to the ones already used in aviation and several directional antennas which could be of different type.

III. ARPAM: ON DEMAND OPERATIONS

We assume that on demand operations are used when an aircraft wishes to communicate with another aircraft which cannot be served from a backbone node or when simply there is a communication need between two aircraft. As illustrated in Fig.1, when node C requests a communication route towards node E, the ARPAM protocol broadcasts a route request (RREQ) message, similar to the AODV routing protocol, through the omni-directional link. RREQ messages contain geolocalization information such as position co-ordinates and velocity vectors. This information is needed in calculating the current position of the originator node since after the originator emitted a packet, its position may have considerably changed and a directional link may not be possible to be established using the node’s old geographic position. Additionally, it is needed in order to provide the total distance that the packet has traveled, which is used as a metric during the routing path selection.

The route is acquired when the RREQ packet reaches the destination node itself or an intermediate node which has a recent route (its record in the route table has not expired yet) towards the destination node. Specifically, when the RREQ reaches the destination node, a route reply (RREP) message will be sent back in order to inform the originator node that a valid path towards the demanded destination node is available. The RREP message will be unicasted back to node C through the omni-directional or the directional data-link according to the Link Request field in the RREQ packet and the geographic information that is available. The Link Request is a 3-bit field which is responsible for defining the data-link transmission technology that will be used. The link may be selected either by the application, or by the routing protocol itself depending on quality of service (QoS) parameters. For instance node C, as illustrated in the Fig. 1, wishes to initiate a high bandwidth connection with node E using a directional data-link path. Then, in order to request the use of the nodes’ directional data-links, node C sets the Link Request field to the appropriate value. When an intermediate node receives such a RREQ packet it forwards it (in case of the existence of such link onboard) or discards it (in case of its absence). If a node is the destination node and a directional antenna is present, it replies sending a RREP message using the appropriate data-link in order to verify that the directional data path can be established. When a RREQ message is received, each node caches a route back to the originator of the request so that the RREP can be unicasted from the destination node along a path to that originator using the requested link, or likewise from any intermediate node that is able to satisfy the request.

IV. ARPAM: TABLE DRIVEN OPERATIONS

Time critical applications such as voice over IP (VoIP) and video on demand (VoD) require low response times from the network. The use of on demand protocols is not considered suitable due to the dynamic nature of these protocols, especially when aircraft move in high density continental areas. Table driven protocols provide a rapid response when a route is requested from a node and the route is maintained in the routing table. Each node involved has to maintain a specific number of routes towards backbone node as shown in Fig. 1, where node B is capable of establishing a link through node A towards the HAP.

When an aircraft joins the network, it does not have any available route towards a gateway node and broadcasts network solicitation packets in order to advertise its presence (this process should not be confused with similar techniques utilized in IPv6). When it becomes apprehensible from the other nodes, it receives fragments of the local routing table from its neighbor nodes through update packets (UPD). The completion of the routing table is made by combining all the available fragments that have been received similarly to what is done by the TBRPF protocol. This approach is considered preferable because if the whole network topology was to be transmitted using a single packet to the new aircraft, the instantaneous network overhead traffic would increase prohibitively. The first UPD packet which the aircraft receives when it joins the network is called UPD_TREE and contains a few routes towards the gateway node. The gateway node does not advertise itself continuously because the update packets already contain routes towards it, since the gateway nodes are also diversified from their IP addresses. Also, it advertises itself only for a specific period of time and when it has not yet accepted any connection requests from any aircraft. After this, the joining aircraft receives UPD packets which contain fragments of the rest network topology until the topology tree with routes towards the gateway is completed.

V. ROUTE MAINTENANCE AND EVALUATION

In AODV, HELLO messages are disseminated in a proactive scheme basis. Nodes send the HELLO messages periodically every HELLO_INTERVAL time period. It is possible to decrease the number of these packets using a mechanism which could be considered a combination of the link layer acknowledgement mechanism reported in the dynamic source routing protocol (DSR) [4] along with the network layer acknowledgement mechanism of the AODV protocol.

In ARPAM, if the MAC layer of the nodes which make up a communication path, for instance C – D – E path, keeps reporting to the network layer for a specific amount of time that the connection between nodes C and D is no longer available will effectively cause C and D to send a HELLO packet in order to investigate the integrity of the path. Then, the originator node waits to receive a HELLO-acknowledgment packet from the destination node in order to mark the path as valid. If, after an elapsed period of time, the node has not yet received any acknowledgment packet, it will emit a HELLO message again, waiting this time for a variable number of periods of time. If again the node does not receive an acknowledgment packet, the route will be marked as invalid and the error reporting procedure will be initialized. The exact number of periods is set according to the flight phase of the aircraft and the application which demands the route. Routing overhead has to be reduced in order to provide full bandwidth potential for the use of high bandwidth consuming applications such as VoIP on aircraft which are not equipped with directional antennas. Thus, by increasing the threshold of MAC failure notifications we manage to decrease the total number of HELLO packet retransmissions avoiding the increased overhead they impose. When a HELLO acknowledgment packet is not received the nodes which detect this failure assume that the route is no longer valid. Then they will unicast an error control message to all their neighbors in the precursors list informing them that the route is no longer available in order to remove that route from their routing tables.

VI. COOPERATION WITH EXISTING SURVEILLANCE SYSTEMS

In order to exploit the benefits of the Air Traffic Management (ATM) applications in the routing protocol we take advantage of the Automatic Dependent Surveillance - Broadcast (ADS-B) concept [10]. ADS-B is a cornerstone for the implementation of the free flight concept. It exploits the existing Global Positioning System (GPS) and the Galileo system in order to acquire the precise position of the aircraft. Its functionality is based on the periodic broadcast of valuable information about the position and the velocity of the aircraft to other ADS-B enabled nodes, like aircraft and ground stations, providing airspace awareness to pilots and air traffic controllers.

The ADS-B application is very useful in order to handle the process of neighbor discovery on behalf of the routing protocol and in order to avoid the continuous data flow regarding the geographical information that has to be exchanged. Using the information from the ADS-B and by assuming that the neighbor nodes are within ADS-B data-link range, ARPAM completes the table which contains information about the neighboring aircraft. This geographic information is also necessary for the computation of coordinates, time and velocity of the neighbor aircrafts, as already described in section 2.

VII. SIMULATION

In order to proceed with the simulation of the concept described in this paper we assume a topology (as presented below, in Fig.2) that, although currently not portraying a real world avionics scenario per se, it is attempting to illustrate a future realistic scenario promoting the free flight concept which is deemed sufficient enough to provide proper observations and useful results. The topology consists of twelve nodes, ten of which are performing random movements. Specifically, the nodes are moving in random directions within a field of one thousand by one thousand kilometer square (10^6 squared km) with velocity ranging from four hundred to eight hundred kilometers per hour. The server node performs a specific movement using the trajectory shown in Fig.2, while the client node maintains a specific direction at constant velocity.

Randomness of the nodes' movement is an approximation used which simplifies the simulation scenario without jeopardizing the validity and the usefulness of the results. In this simulation scenario we assume that the client node requests and succeeds on establishing a VoIP session with the server node. The VoIP application has been selected in order to show the network and protocol performance according to the applications' demands.

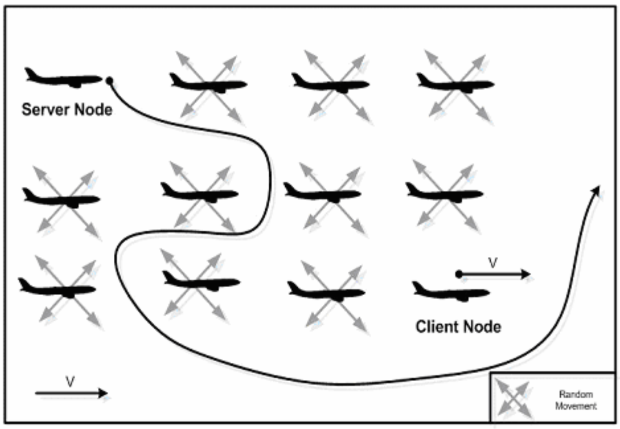

Figure 2. Network topology

The data-links, which the aircraft are equipped with in the simulation scenario, consist of one omni-directional VHF link and one Ka-band directional link. The omni directional link is utilized for the routing protocol traffic while the Ka-band directional link is utilized for the VoIP application data. Using the OPNET Modeler simulation tool [9] we have extracted a set of graphs (Fig. 3 and Fig. 4) which provide a performance comparison of ARPAM, AODV, DSR and TORA routing protocols and their evaluation in respect to the routing overhead experienced. Effectively, the routing overhead is the routing traffic received by the server node and the routing traffic sent by the server node respectively.

In the figure above (Fig. 3) the routing overhead sent by the server node is illustrated. In the majority of time the TORA routing algorithm exhibits slightly better performance compared to the other protocols, including ARPAM, but there are some time periods that its maximum overhead is considerably greater in comparison with all the rest. The ARPAM protocol exhibits a much more stable behavior compared to TORA while its performance is considerably better than AODV and DSR. Although the ARPAM packets have higher overhead due to the excess of the geographical information included, the route maintenance algorithm ensures less routing overhead than the AODV routing protocol.

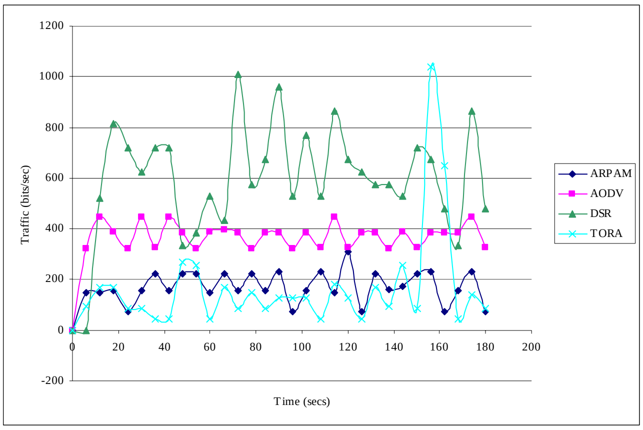

Figure 3. Routing traffic transmitted by Server node

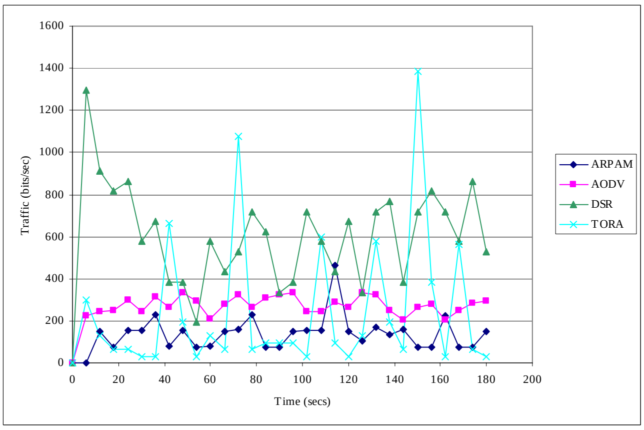

Figure 4. Routing traffic received by the Server node

Fig. 4 illustrates the routing overhead received by the server node. It can be easily seen that the ARPAM protocol produces lower overhead compared to DSR and AODV, while exhibiting a much better behavior compared to TORA. Additionally, the graph highlights the fact that ARPAM excels in performance and stability combined, when compared to its rivals.

VIII. CONCLUSIONS

In this paper we have presented and described the ARPAM routing protocol correlation to the existing avionics technology and effectively we compared it to antagonistic routing protocols. Even though the simulation results show only a small fraction of its capabilities in routing, the ARPAM currently exhibits a very stable and high performance behavior for routing in aeronautical MANETs. It has to be noted that, compared to the typical real world avionics flight plans, the topology we describe in this paper is relatively more complex but nevertheless the performance of the protocol compared to alternative MANET protocols is promising.

Although the current implementation is not considered mature enough, ARPAM indeed appears very competitive to the other protocols. Obviously, there is still room for improvement and our goal is to further develop ARPAM and provide future simulations which will include more complex network topologies and scenarios closer to the future aviation environment. We are continuing our work in extending the capabilities of the working model and also extending its internal routing mechanisms for increased reliability on critical applications and additional stability.

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