A-GR: A Novel Geographical Routing Protocol for AANETs
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Abstract
With the rapid growth of general aircraft and lack of ground facilities, air traffic control and aeronautical communication system face huge pressure, especially in low-altitude airspace. Aeronautical ad hoc networks (AANETs) are large scale multi-hop wireless network of aircraft, which could provide direct air-to-air communication between aircraft without ground infrastructures. However, the features of aircraft node present a great challenge to provide efficient and reliable data packet delivery in AANETs. In this paper, we present an Automatic dependent surveillance-broadcast (ADS-B) system aided geographic routing protocol (called A-GR) for AANETs. The proposed A-GR uses the position and velocity of aircraft provided by airborne ADS-B system to eliminate the traditional routing beaconing and presents a velocity-based metric for next hop selection, which could adaptively cope with the fast moving of aircraft and dynamic changes of network topology. Many simulations are performed and the results show that the proposed A-GR can effectively decrease the routing overhead, improve the packet delivery ratio and make good use of the network resources.

Keywords: Aeronautical ad hoc network, Geographic routing protocol, Automatic Dependent Surveillance-Broadcast.

1 INTRODUCTION

With the rapid development of global air transport industry and the open of low-altitude in the next 20-30 years, the number of aircraft grows fast and the low altitude airspace is increasingly complex. And, air traffic control and aeronautical communication face great pressure as lack of corresponding ground facilities [1]. Aeronautical ad hoc networks (AANETs) are decentralized wireless networks formed by highly mobile aircraft connected via long range data-links. AANETs could greatly reduce the dependence to ground facility and expensive satellite. Thus, some related projects are carried out recently, such as ACAST [2] and NEWSKY [3]. The self-organizing multi-hop feature of AANETs could expand the connectivity over line-of-sight (LOS) limitation of radio and help the pilots to extend the communication scope, especially under the circumstances of infrastructure-less areas, such as mountains, deserts and the sea.

As the general aircraft in low-altitude have large difference in velocity, avionics and flexibility, limited bandwidth, high flight density and connectivity restrictions represent the main bottlenecks in aeronautical communication, which make AANETs in low-altitude areas tend to lose packets. Especially, fast moving nodes and frequent topology changes create a unique challenge for routing packets. Thus, providing more suitable mobile routing technique to guarantee reliable delivery of packets is a challenge.

Among Mobile Ad-hoc Network (MANET) routing protocols, geographical routing protocol requires only the position information of one-hop neighbors and forwards a packet to the direction of its destination. It does not need to maintain routing table and set up routes for routing. Thus, it shows good performance in many studies. Greedy Perimeter Stateless Routing (GPSR) [4] was one of the most famous geographic routing protocols, which has also inspired some extensions in aeronautical networks. B. Karp and H. T. Kung et al. [4] presented a novel routing protocol for wireless datagram networks that uses the positions of routers and a packet’s destination to make packet forwarding decisions, called Greedy Perimeter Stateless Routing (GPSR). GPSR makes greedy forwarding decisions using only information about a router’s immediate neighbors in the network topology. When a packet reaches a region where greedy forwarding is impossible, the algorithm recovers by routing around the perimeter of the region. By keeping state only about the local topology, GPSR scales better in per-router state than shortest-path and ad-hoc routing protocols as the number of network destinations increases. Under
mobility’s frequent topology changes, GPSR can use local topology information to find correct new routes quickly. GLSR \[5\] used a geographic load share routing metric to avoid link congestion. D. Medina et al. \[5\] pointed that broadband air-to-air communication requires a medium access control (MAC) protocol capable of handling high traffic loads in the network and providing quality-of-service (QoS) guarantees to communicating nodes. Carrier sense multiple access (CSMA) techniques are inappropriate in this environment, since their performance degrades significantly as the traffic load and network size grow due to increased probability of collisions and the presence of hidden terminals. Aircraft are equipped with GPS for navigation purposes, and this provides a global time reference that can be exploited for channel access synchronization among network nodes, e.g., to schedule collision-free transmissions in a time division multiple access (TDMA) fashion. Hyeon et al. \[6\] proposed a new geographic routing protocol that can cope with dynamic topology changes adaptively. The revised protocol makes use of mobility information, which is updated frequently by the base station on the ground. This protocol is based on geographic routing protocol because it is good for high dynamic topology change. To accommodate the new properties of aircraft ad hoc networks, a hybrid-forwarding scheme is proposed, which makes use of mobility patterns obtained by aircraft-to-ground communication. Moreover, when it is impossible to utilize the mobility pattern, a forwarding scheme based on neighboring table with direction is proposed. However, above geographic protocols have their own advantages, but they are all lack of good supports for high-speed node mobility and fast topology changes in practice.

In this paper, we propose an ADS-B (Automatic Dependent Surveillance-Broadcast) aided geographic routing protocol (called A-GR). As the evolution of traditional airborne radar, airborne ADS-B system can provide more rich and accurate flight information. By integration the ADS-B system into the routing system, the proposed A-GR uses the position and mobility information provided by ADS-B system to establish neighbor table and select next hop, which eliminates the routing beaconing scheme and could effectively decrease the routing overhead, improve the packet delivery ratio. Many simulations are performed, and the results show that the proposed routing protocol significantly reduces the network overhead and packet loss probability.

The remainder of this paper is structured as follows. Section 2 introduces related background. Section 3 proposes a novel ADS-B aided geographic routing protocol, i.e., A-GR. Section 4 evaluates the performance of the proposed routing protocol. The paper concludes in Section 5.

2. BACKGROUND

An aeronautical ad hoc network is composed of \(N\) identical airplane nodes utilizing half-duplex transceivers on the common channel. AANETs can be modeled as an undirected connectivity graph \(G(V,E)\), where \(V\) is a finite set of aircraft, and \((i,j)\in E\) represents a wireless link between aircraft \(i\) and \(j\) \((i \neq j)\). A function is used to indicate an aircraft node’s mobility condition in the network, that is

\[
F(t) = f[x(i,t),y(i,t),v(i,t),\theta(i,t),R_i] \tag{1}
\]

where \((x(i,t),y(i,t))\) is the position, \(v(i,t)\) is the speed, \(\theta(i,t)\) is the moving direction of aircraft \(i\) at time \(t\) and \(R_i\) is the communication range of aircraft \(i\). The mobility model eliminates the need for directon variables entirely, along with the trigonometric calculations that would the required to determine the node velocity vector and more information about the dynamic movement model of aircraft can be found in \[7\].

In the regions lacking ground facilities, especially over mountains, deserts or oceans, High Altitude Platform Station (HAPS) is gradually used as air base station for air traffic control due to its large-area coverage, low cost and rapid deployment \[8\]. As an alternative for ground station or satellite, HAPS could aggregate and translate ADS-B and radar messages for aircraft equipped with different data-link technologies \[9\]. Thus, HAPS (with air base station) and aircraft within its coverage compose an integrated communication and surveillance system.

As depicted In Fig. 1, HAPS is deployed in order to expand the coverage of ADS-B, and realize communication between aircraft equipped with different type of ADS-B devices. The ADS-B message of different aircraft are converged by HAPS and then broadcast to other aircraft. All the information from the different types of ADS-B systems can be shared by means of redistribution from the HAPS control facility. The beyond line-of-sight communication through AANETs can provide efficient message dissemination to other aircraft or remote command centers.
2.1 ADS-B system

ADS-B is a cooperative surveillance system for air traffic management (ATM). An aircraft equipped with the ADS-B system broadcasts the state vector such as ID, position, velocity, altitude, and other flight-related information, which is far richer than the traditional radar technology. The radio range of ADS-B system is adjustable by the power control mechanism. The state vector of ADS-B messages is obtained from multiple sensors in the aircraft and the message is broadcast by the ADS-B transmitting subsystem. Other aircraft or ground control facilities within the radio range can hear ADS-B messages. The received ADS-B message is analyzed by the receiving subsystem and then distributed to on-board applications.

Fig. 2 shows the transmission and reception of ADS-B messages. Cockpit Display of Traffic Information (CDTI), which receives and displays the information from ADS-B messages, could effectively enhance the ability of collision avoidance and situational awareness for all participants. Three main different types of ADS-B systems are 1090MHz Mode S Extended Squitter (1090 ES), Universal Access Transceivers (UAT), and VHF Data Link Mode 4 (VDL Mode 4). Commercial flights will use 1090 ES while general aviation flights will employ UAT. VDL Mode 4 is currently studied in Europe and China.
2.2 Aircraft flight mode

During the packet delivery in AANETs, the changes of aircraft trajectory will affect the accuracy of routing protocol. Thus, the accuracy of aircraft mobility is very important because all traffic advisories are based on the current state estimates of the aircraft. Clearly, a major challenge in aircraft tracking is thus to provide accurate state estimates of aircraft. However, it is difficult to obtain precise aircraft state estimates when the aircraft changes a flight mode.

It can be assumed that the general aircraft in low-altitude airspace have two flight modes: Constant Velocity (CV) mode and Coordinated Turn (CT) mode. CV mode consists of its position and velocity. Angular velocity is included in target dynamics besides the position and velocity for CT mode. The flight of aircraft is described as CV model generally, when aircraft encountered turning, flight mode will be converted to CV. And they will be back into CV model if normal status is recovered. The continuous-time dynamic models are given by [10].

CV mode is as follows:

\[
\dot{x}(t) = \begin{bmatrix} 0_{3 \times 3} & I_{3 \times 3} \\ 0_{3 \times 3} & 0_{3 \times 3} \\ 0_{3 \times 3} & I_{3 \times 3} \end{bmatrix} x(t) + \begin{bmatrix} 0_{3 \times 3} \\ 0_{3 \times 3} \\ I_{3 \times 3} \end{bmatrix} w(t)
\]

(2)

where \( x = [x \ y \ z \ \dot{x} \ \dot{y} \ \dot{z}]^T \).

CT mode is as follows:

\[
\dot{x}(t) = \begin{bmatrix} 0_{3 \times 3} & I_{3 \times 3} & 0_{3 \times 3} \\ 0_{3 \times 3} & 0_{3 \times 3} & 0_{3 \times 3} \\ 0_{3 \times 3} & 0_{3 \times 3} & 0_{3 \times 3} \end{bmatrix} x(t) + \begin{bmatrix} 0_{3 \times 3} \\ 0_{3 \times 3} \\ I_{3 \times 3} \end{bmatrix} w(t)
\]

(3)

where \( x = [x \ y \ z \ \dot{x} \ \dot{y} \ \dot{z} \ \omega_x \ \omega_y \ \omega_z]^T \), and

\[
W = \begin{bmatrix} 0 & -\omega_z & -\omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix}.
\]

Here, \( \Omega = [\omega_x \ \omega_y \ \omega_z] \) is the angular velocity vector and \( w(t) \) is the process noise. The equivalent discrete-time dynamic model can be derived with Taylor-series [11].

During the flight, aircraft generally move along the predetermined route with uniform linear motion. Acceleration is often seen as a random disturbance input, and is assumed to obey zero-mean white Gaussian distribution. However, there will be some steering for aircraft in low-altitude airspace, such as slow changes in mobility to avoid other aircraft or obstacles, or atmospheric turbulence and gusts encountered, so as to bring the acceleration.

3. PROPOSED A-GR PROTOCOL

This paper focuses on the special characteristics of aircraft nodes because they are equipped with ADS-B system, and emphasizes on high mobility of aircraft. Then, an ADS-B aided geographic routing (A-GR) protocol is presented, which makes use of the position and mobility information provided by ADS-B system to improve the performance of geographic routing protocol for AANETs.

As shown in Fig. 3, the proposed routing protocol is composed of three parts that work together in AANETs. The first part is neighbor discovery, in which we use the position provided by ADS-B system to eliminate the traditional hello routing beacon (Section 3.1). The second part is next hop decision (Section 3.2), in which we present a velocity based metric to select the more suitable next hop. In the third part, we discuss the data forwarding strategy (Section 3.3).

![Fig. 3. Procedures of ADS-B aided geographic routing protocol](image)

3.1 Neighbor discovery

Geographical routing protocol has a neighbor discovery phase in order to choose the suitable next hop. Every node receives hello beacons from its neighbors and maintains its own neighbor table. The accuracy of the neighbor table increases when the beacon interval is shortened. However, the beaconing overhead is also increased, which would reduce the throughput for data packets and raise the probability of collision in the network.

![Fig. 4. Integration of ADS-B messages into A-GR protocol](image)
ADS-B receiving subsystem. A-GR builds the neighbor table based on the ADS-B messages received from the neighbor aircraft, which include the position and vector state of aircraft. The beaconing overhead of traditional geographical routing protocol is totally eliminated, when ADS-B messages instead of traditional hello beacons are used to find neighbor nodes. As ADS-B system and AANET use their own physical layer antenna, ADS-B messages do not interfere with data packets for routing. The neighbor table is updated every second according to the ADS-B message cycle.

### 3.2 Next hop decision

In AANETs, the Euclidean distance \((EU)\) and relative velocity \((RV)\) between two nodes \(i, j\) are as follows:

\[
EU_{i,j}(t) = \sqrt{(x_i(t) - x_j(t))^2 + (y_i(t) - y_j(t))^2 + (z_i(t) - z_j(t))^2}
\]

where \((x_i(t), y_i(t), z_i(t))\) and \((x_j(t), y_j(t), z_j(t))\) are the positions of node \(i\) and \(j\) at time \(t\).

\[
RV_{i,j}(t) = \frac{\|\mathbf{v}_i(t) - \mathbf{v}_j(t)\|}{d_{i,j}(t)}
\]

where \(\mathbf{v}_i(t)\) is the velocity of node \(i\) at time \(t\)

In traditional geographical routing protocol, such as GPSR, packets are usually forwarded to the neighbor that is geographically closest to their destination. But, in A-GR, the high mobility of aircraft is also taken into consideration in next hop selection. In order to better adapt the fast-moving aircraft, we define the instantaneous flight time \((IFT)\) of an aircraft \(i\) to \(j\) toward destination \(D\) as follows:

\[
IFT_j = \min_{k \in N_i} \frac{\Delta d_{i,k}(t,D)}{RV_{i,k}(t,D)}
\]

where \(N_i\) is the neighbor set of node \(i\), \(R\) is the transmission range of the node \(i\).

A-GR forwards the packets arriving at node \(i\) to the next hop by using this metric. IFT is a velocity based metric used for next hop selection decisions in A-GR. By using the position and mobility information from ADS-B messages, a source node calculates the IFT of its neighbors to understand which will potentially be the soonest to reach the destination.

Traditional geographical routing protocols, in which distance is used as the only metric for route decision, are lack of support for the mobility of mobile node. This is because the selected next hop is the one with the best advance toward destination, as in GPSR, and also takes into the velocity of aircraft into consideration to improve the performance. Thus, the solution adopted by A-GR is to minimize the ratio between advance and relative velocity, represented by the IFT metric. In this way, A-GR considers the mobility status of all neighbors with positive advance, choosing at any time the next hop with the shortest time toward the destination.

### 3.3 Data forwarding

When receiving a data packet, node \(S\) uses its neighbor table to decide how to route the packet. For the case when there are often several nodes within the transmission range of node \(S\), the one with the best IFT will be chosen as the next hop. If there are no nodes within the transmission of the node \(S\), the packet will be buffered and queued for a configurable amount of time, until suitable nodes are encountered. Otherwise, the packet will be dropped.

### 4. PERFORMANCE EVALUATION

To evaluate the performance of the proposed A-GR routing protocol, many simulations are performed and the results are averaged and compared with GPSR [4] and GRAA [6].

A dynamic simulation environment is set up by using QualNet 5.0 (discrete event network simulator) [12]. The simulation environment consists of a set of wireless mobile networking extensions, and provides a detailed simulation model of every aircraft node.

At the physical layer, realistic modeling of
low-altitude aeronautical communication environment factors is provided, such as free space propagation, transmission power, antenna gain and receiver sensitivity [13].

At the link layer, we model the complete distributed TDMA based media access control (MAC) protocol. The application layer uses CBR protocol to simulate the aeronautical communication traffic.

Table 1  Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network size</td>
<td>20 km×20 km</td>
</tr>
<tr>
<td>Packet mean size</td>
<td>512 kbytes</td>
</tr>
<tr>
<td>Sending rate</td>
<td>200 kb/s</td>
</tr>
<tr>
<td>Antenna coverage range</td>
<td>15 km</td>
</tr>
<tr>
<td>Transmit RF power</td>
<td>125 w</td>
</tr>
<tr>
<td>Receiver sensitivity (S/N=6dB)</td>
<td>-24.67 dBm</td>
</tr>
<tr>
<td>Aircraft average speed</td>
<td>250 m/s</td>
</tr>
<tr>
<td>Transmitter/Receiver antenna</td>
<td>Omnidirectional</td>
</tr>
<tr>
<td>Mobility model</td>
<td>Gauss-Markov</td>
</tr>
<tr>
<td>Simulation time</td>
<td>10 minutes</td>
</tr>
</tbody>
</table>

4.1 Simulation setup

All aircraft nodes are taking random movement at the altitude of 3km with assigned speed. A Gauss-Markov mobility model [7] is used in this paper, which could provide more realistic aircraft movement. The Gauss-Markov mobility model is a relatively simple memory-based model with a single tuning parameter, $\alpha$, which determines the amount of memory and variability in node movement. In the implementation, each mobile node is assigned an initial speed and direction, as well as an average speed and direction. At set intervals of time, a new speed and direction are calculated for each node, which follow the new course until the next time step. This cycle repeats through the duration of the simulation. The new velocity and direction parameters are calculated as follows:

\begin{align*}
    v_t &= \alpha v_{t-1} + (1-\alpha)\tilde{v} + \sqrt{(1-\alpha^2)}v_{x(t-1)} \\
    d_t &= \alpha d_{t-1} + (1-\alpha)\tilde{d} + \sqrt{(1-\alpha^2)}d_{x(t-1)} 
\end{align*}

where $\alpha$ is the tuning parameter, $\tilde{v}$ and $\tilde{d}$ are the average velocity and direction parameters, and $v_{x(t-1)}$ and $d_{x(t-1)}$ are random variables from a Gaussian normal distribution that give some randomness to the new velocity and direction parameters. Generally, $\alpha$ is set between zero and one, which allows for varying degrees of randomness and memory. In our simulation, $\alpha$ is set to 0.5.

The number of aircraft node in simulation is varied from 20 to 80. A stationary HAPS node is located at 10 km altitude in the center of the simulation area representing the air station. The parameters in simulation are given in Table 1.

4.2 Simulation results and analysis

Three metrics are defined to measure the performance of the different routing protocols as follows:

1) Overhead: The excess packets used to move the actual packet payload from source to destination. This metric measures the amount of control packets generated by the routing protocol for neighbor discover.

2) Packet delivery ratio (PDR): The ratio of the number of packets received by the sink at the destination and the number of packet sent by the source at the application layer. This is a good metric to measure the quality of a route in a highly dynamic topology change environment. The better the scheme is, the higher the PDR is.

3) Delay: The time required to transmit a data packet from source to destination. It includes the latency for route discovery, the time spent in the queues of intermediate nodes and the time to cross all the hops from the source to the destination.
4.2.1 Simulation results on Overhead

Fig. 4. shows the average overhead of the network increases with the node density. In the simulation, the overhead includes the ADS-B service (location and mobility information) and hello beacon messages. As the proposed A-GR take advantage of the information from ADS-B system as opposed to hello routing beacons for neighbor discovery, it behaves the minimum control packet overhead among the three schemes. In contrast, GPSR and GRAA need to send periodic hello beacons for proactive neighbor discovery in rapid changes of network topology.

Hence, the overhead of them continues to exponentially increase as the number of nodes increase. The overhead of the proposed A-GR increase linearly, not as drastically as GPSR and GRAA, from around 0.3 Mb/s at 10 nodes to around 3.3Mb/s at 80 nodes.

4.2.2 Simulation results on PDR

As shown in Fig. 5, the PDR of the proposed A-GR maintains a high level with the exception of slight performance degradation as the number of nodes approaches 50 and higher. In contrast, the PDR for both GPSR and GRAA immediately degrades, which is most likely due to the rapid increase in
overhead as the number of nodes increases. Rapid growth of overhead (hello beacon messages) is easy to consume the bandwidth, saturate the queues, and thus cause rejection of packets. Because it uses the ADS-B message packets to locate and then with the increasing number of aircrafts, the number of ADS-B messages also increases sharply. Hence, the PDR values will begin to decline after a threshold.

As the proposed A-GR protocol don’t need to produce large quantity of hello routing beacons, an d hence, the trend of delay for GPSR and GRAA increases in delay. A-GR routing protocol is able to get its buffered packets to destinations more quickly as the node density increases, perhaps the increased nodes provide more options to choose suitable next hop. On the contrary, as the increase in nodes results in more hops and overhead for GPSR and GRAA, the queues of them are likely to congestion due to the high traffic load of network.

Hence, the trend of delay for GPSR and GRAA increases as the number of nodes increases. But, when the number of nodes is lower (below 40), the delay of A-GR is almost like GPSR and its advantage is not obvious.

4. CONCLUSIONS

AANETs can be a good perspective and practical model to deploy ad hoc network technology, but, they have many unique features in aeronautical communication, especially for general aircraft in low-altitude airspace. Thus, it is essential to develop specific routing technology to meet the requirements for AANETs [14-18].

In this paper, we present a novel ADS-B aided geographical routing protocol for AANETs, which uses the position and mobility information provided by airborne ADS-B system to improve the performance of communication. Many simulations are performed and the results verify that the proposed A-GR routing protocol has better performance: 1) it could effectively decrease the routing overhead as the number of nodes increases; 2) it could provide better packet delivery ratio and end to end delay while facing frequent topology changes; 3) the improved protocol can be achieved directly and easily without large transformation of existing equipment.

The work could provide better aeronautical communication application in increasing complex low-altitude airspace. In the future, the mobility model of aircraft will be the focus on WSN environment [19-21]. Moreover, more analytic results about the impact of the proposed scheme on the delay-throughput tradeoff will be performed.

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